PRODUCTION, CHARACTERISATION AND ECONOMIC VALIDATION OF FUEL PELLETS FROM CASSIA TORA (*TAFASA IN HAUSA LANGUAGE*) FOR DOMESTIC AND INDUSTRIAL APPLICATIONS

Ibrahim U Aikawa

A thesis submitted in partial fulfilment of the requirements of the University of Wolverhampton for the award of the degree of Doctor of Philosophy

February, 2016

UNIVERSITY OF WOLVERHAMPTON, WULFRUNA STREET,

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DEDICATION

This thesis is dedicated to Muhammad (SAW) and his progeny, and to the memory of my late parents, Mallam Usman Ibrahim Dangaske and Hajiya Amina (Asabe) Sule Mazawaje.

DECLARATION

This work or any part thereof has not previously been presented in any form to the University or to any other body whether for the purposes of assessment, publication or for any other purpose (unless otherwise indicated). Save for any express acknowledgements, references and/or bibliographies cited in the work, I confirm that the intellectual content of the work is the result of my own efforts and of no other person.

Signature ……………Ibrahim U Aikawa…………………………..

Date …………………10/02/2016………………………………

PUBLICATIONS

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ABSTRACT

A laboratory scale method was used to produce pellets from cassia tora stems with pelletizing temperature conditions of 30, 45, 60, 75, 90, 105 and 120^oC under a pressure of 50, 70, 90,120 and 140 MPa. A total of 30 pellets were produced under each condition of production. The physical and chemical properties of the pellets were investigated. The pellets produced under $\leq$75^oC and $\leq$90 MPa were found to have durability $\leq$90 %. A Bulk density range of 617 to 619 kgm-^{3} was measured for all the produced pellets irrespective of production conditions. The pellets produced in the range of 50 MPa/30^oC-140 MPa/120^oC were found to have a moisture content ranging between 7.18- 9.6 %. Ash content of 4.2 % was achieved using both Thermogravimetry (TGA) and CEN/TC 335 standard. The gross calorific value of the pellet was determined to be in the range of 17.89-18.1 MJ/kg. TGA results also indicates low moisture and ash content and the process of pyrolysis occurred at 137-550^oC at 10^oC/min heating rate. The activation energies and reactivities determined from TG/DTG curve are 72.01, 106.81 and 88.67 kJ/mol and 1.76 E+19, 5.1 E+06 and 3.92 E+05 for step I, II and III respectively. A water boiling experiment was carried out to evaluate the cooking efficiency of the pellets compared to fuel wood, kerosene and liquefied natural gas (LPG). The energy intensities and energy cost of 1.2, 0.78, 0.56 and 1.36 kJ/g of water and 0.2, 0.7, 0.4 and 0.2 Nigerian Naira (₦) were calculated for fuel wood, kerosene, LPG and the pellets respectively.

An economic analysis of fuel pellet production from Cassia tora stems has been carried out for conditions found in Kano state, Nigeria. The total production cost, for a base case scenario of 5t/h and operating for 270 days a year, is £4/tonne (1094.5 Naira/ton) of pellets. A ‘Willingness to pay’ analysis was also performed using the Contingent Valuation Technique. A structured contingent valuation questionnaire was administered to 420 randomly selected households in the Kano metropolis and Chi-square analysis was conducted on the data collected. The results of the analysis, at a 5 percent (0.05) confidence level, showed that p-values were less than 0.05 (0.05>p) for all the responded variables. It is confirmed, from the analysis, that an inadequate supply of energy is a statistically significant problem in Kano state and households significantly use fuel wood for domestic energy applications. The results also indicated the willingness of households to switch to a new product and were willing to pay a mean amount of £5 (1361.5 Naira) for a ton of the fuel pellets. Properties of the cassia tora pellets were found to be comparable with other biomass fuel pellets. It is recommended that policy and investment should be geared towards fuel pellet production in Nigeria, to address problems of energy poverty and environmental deterioration, and provide a means for further economic development.

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LIST OF ABBREVIATIONS

Age	Age of household
ASABE	American Society of Agricultural and Biological Engineers
BSE	Back-scattered
CEN/TC	Technical Committee Developing Standards for all forms of Solid Bio-fuels within Europe
C: N	Carbon and hydrogen ratio
CTS	Cassia tora stem
C.V.	Calorific value
CV	Contingent valuation
d.b.	Dry basis
DC-CVM	Dichotomous choice contingent valuation method
Df	Degree of freedom
DIN	German Standard for solid Bio-fuels
d.m.	Dry matter
Du	Mechanical durability
DTA	Differential thermogravimetic analysis
DTG	Derivative thermogravimetic analysis
Edu	Household educational level
EFS	Energy fuel supply
FAO	Food and Agricultural Organisation of the United States
FBC	Fluidised Bed Combustor
FS	Family size
G.C.V.	Gross calorific value
Gend	Household gender

HHV	Higher heating value
HWTP	Household willingness to pay
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
IEA	International Energy Agency
Inc	Household income
LHV.	Lower heating value
N.C.V	Net calorific value
OM	Organic matter
ONORM	Austrian Standard for Solid Bio-fuels
Ppm	part per million
RH	Relative humidity
SE	Secondary electron detector
Sem	Standard error of the mean
SEM	Scanning Electron Microscopy
VM	Volatile matter
w.b.	Wet basis
wt%	Percentage of weight
WTP	Willingness to pay
XRD	X-Ray Diffraction
X^2test	Chi-square test
PBP	pay back period

LIST OF SYMBOLS

A_d	Die cross-sectional area (m^2)
A	Exponential factor (s^{-1})
F	Total resistance force (N)
P	Applied compression (MPa)
V	Volume (m^3)
ρ	Bulk density (kg/m^3)
η	Efficiency (%)
C_p	Specific heat capacity of water at constant pressure (J/kgK)
T_b	Boiling temperature (K)
T_o	Initial water temperature (K)
L	Latent heat of vaporisation of water (kJ/kg)
M_f	Mass of fuel burnt (kg)
M_c	Mass of water evaporated (kg)
$\mathcal{E}_f$	Caloric value of the fuel (kJ/kg)
M_w	Mass of water (kg)
E_a,	Activation energy (kJ/mol)
R	Molar gas constant (J/Kmol)
t.	Time (s)
w	Weight of sample at time t
wo	Initial weight of sample (kg)
wf	Final weight of sample (kg)
α	Change in weight of sample at the stage of pyrolysis

μ Error term or random variable.

C_c Capital cost (~~₦,~~ €, £ or $)

e Capital recovery factor

C_{eq} Equipment cost (~~₦,~~ €, £ or $)

i Interest rate

α_{eq} Unit cost of equipment (~~₦,~~ €, £ or $)

C1,2.. Equipment capacity (output/time)

CT Total capital cost (~~₦,~~ €, £ or $)

C_{op} Operating cost (₦)/year)

T_{op} Total operational hours of plant per year (hrs/yr)

G_p Production rate (tonne/ h)

C_p Production cost (₦ /tonne)

ELEMENTS

C Carbon

H Hydrogen

N Nitrogen

S Sulphur

O Oxygen

K Potasium

Zn Zinc

As Arsenic

Pb Lead

Cr Chromium

Cl	Chlorine
Cu	Cupper

1. INTRODUCTION

1.1 Background of the study

Environmental issues coupled with the exhaustible nature of fossil fuels and the volatile nature of its market and the need for an independent energy supply to sustain economic development are major reasons for the world-wide calls for sustainable and renewable-energy resources. Biomass constitutes a great source of energy in most areas of the world, especially in developing countries. Fuel wood is the predominant energy source in Nigeria accounting for 83 percent of the entire energy consumption (Momodu, 2013; UECD/IEA, 2007; Sambo, 2005) with about 50 million tons consumed annually (Edward and Paul, 2013; Sambo, 2006). Domestic energy accounts for more than 50 percent of the whole energy consumed in Nigeria (Momodu, 2013; Sambo, 2005) out of which about 70-80 percent of households depend on fuel wood as their cooking fuel (Momodu, 2013; CIFOR, 2005).). The consequences of this to the natural environment include deforestation, and this encourages desertification, soil erosion and loss of soil fertility (Sambo, 2001). According to Babanyara and Saleh (2010), Nigeria lost about 6,145,000 hectares of forest between 2000 and 2005 alone. Fuel wood consumption in Nigeria has therefore exceeded sustainable production, especially in the Northern part of the country where the area is facing increasing desert encroachment (Anozie *et al.*, 2007).

The Human Poverty Index (UNDP, 2009) data revealed that poverty is more common in Northern Nigeria than in the South with a very low human development index which could be as a result of energy poverty (Ali and Richard, 2013).

The Northwestern part of Nigeria has the highest human population (NPC, 2006) in the country but receives only about 5.9 percent (Ali and Richard, 2013) of the total supply of fossil fuel (kerosene and liquefied petroleum gas) thereby making the region prone to energy poverty. The decreasing availability of fuelwood and the menace of desertification, coupled with ever fluctuating prices and inadequate supply of kerosene and cooking gas in the region, requires alternative sources of energy to be found.

According to Okoroigwe (2008) crop residues and waste result in 6.1 million tons of dry matter produced annually in Nigeria whose energy content is approximately 5.3×10^{11} MJ and this is not properly utilised. Some of these crop residues and wastes gradually flow through the environment adding to the waste stream or are locally burnt thus causing environmental air pollution.

There is 13.43 Tg (representing 157.8 PJ of potential energy) of field residue ready for use in Northwestern Nigeria for energy conversion (Edward and Paul, 2013). Even though there is such a huge amount of agricultural residues with considerable potential available for bio-energy production, there is competition as the residues are usually used for poultry, and animal feeds. About 80 percent of the land mass cultivated support's cereal crop production and cereal residues are often converted into animal feeds (Mohammed *et al.*, 2014). Some available residues are burnt on the farms to allow further cultivation of the soil, while some residues are neglected and form part of a solid waste stream. According to Kano State Ministry of Agriculture (KNMANR, 2014), a large part of the residue/farm waste is from cassia tora plant remains, a known farm weed that grows in every unattended and cultivated land in the entire Kano state and Northwestern region. Densifying such plant material into energy products like fuel pellets is one of the best ways of solving the problem of energy supply within the region. Crop residues/waste can be converted into fuel pellets and therefore, help in pollution control by avoiding unnecessary bush burning and can help reduce the dependency on fuelwood and hence promote better environmental sustainability. It will also provide a market for the fuel pellets which in turn can aid the economic development of the region.

Agricultural residues can be processed into upgraded fuel products such as briquettes, e.g. sawdust, cowpea chaffs, corncobs, and water hyacinth (Olorunnisola, 1999). In Nigeria, briquettes have been produced with the aid of binders such as cassava starch and palm oil sludge, but these binders tend to produce smoky briquettes (Olorunnisola, 2007; Yaman *et al.*, 2000). Yaman *et al.* (2000) reported that waste paper could be mixed with other biomass materials to produce durable and smokeless fuel briquettes. However, pellets could be cheaper in terms of energy requirement to produce, ease in transportation and storage, and more convenient when used in combustion equipment (Adapa, 2011; Zamorano, 2011; Nolan *et al.*, 2010; Miranda *et al*., 2009).

Biomass fuel pellets, produced from residues/wastes, compete with other energy sources (Ryu *et al*., 2006). The factors that must be considered are the heating value of biomass per unit volume, low moisture content, efficiency in burning, low ash content and particulate emission content. Transportation costs also need to be taken into consideration, in the economic argument, as these costs should be lower for biomass fuel pellets, sourced and produced locally in comparison to that required for coal and oil fuels. Pellets can have a variety of applications from small-scale residential heating to large-scale co-firing in coal power plants (Wahlund *et al*., 2004).

Though pellet production has gained recognition as an international trade with a market size increasing annually (Junginger *et al*., 2008; Savalainian, 2007), there is no evidence of fuel pellet production in Nigeria, which could contribute to address the issue of insufficient supplies of energy for both domestic and industrial applications. Developing countries like Nigeria need to put efforts towards fuel pellet production to utilise the abundant available resources of biomass raw materials from its' crop residues/waste; this is especially true for the Northern part of the country where the majority population are experiencing a crisis with a deficient energy supply.

1.2 Cassia tora (*tafasa* in Hausa language)

Cassia tora is a dicot legume that grows as a legume medium (see figure 1.1). The plant is an herbaceous annual foetid herb, which can grow 30-90 cm high, consisting of alternative pinnate leaves with three opposite pairs that are obovate in shape with a round tip (Chi-Hao *et al*, 2004). The plant is found on the plane lands of northerly Nigeria, occupying about 45 percent of the virgin lands that are left unattended (Chidume *et al*., 2002; Ajulo *et al*, 1989). It is a stress tolerant and easy to grow plant that grows in dry soil throughout tropical parts and high hills. Cassia tora is widespread in Kano state, as it grows as a legume weed in farmland, thereby competing with ground nuts, beans and other leguminous food products (Cock and Evans, 2008; Usman and Omotayo, 2007). Kano rich and fertile soil favours the spontaneous growth of cassia tora around the state. Its removal from farmland results in an increase in solid waste stream across the state.

Figure 1.1: Cassia tora dry plant with the leaves, pods and stem.

Cassia tora is an important plant in the Northern part of the country due to the amount of waste it produces annually, and the activities involved in the clearance and burning of the plant remains (REMASAB, 2014; Ibrahim *et al*, 1983). Although not purposely planted, information gathered from interactions with farmers and other stakeholders indicate that a lot can be expected, in economic returns, from cassia tora when sowed in the future for energy purposes.

1.2.1 Cassia tora and solid waste management in Kano State

Wood residues produced from wood products industries, agricultural residues produced by agro-industries and farms, and energy crops all contribute to the generation of municipal solid waste (Otoniel *et al*., 2001). In developing countries where waste management systems are insufficient and inefficient, coupled with an expanding urban population, the 'waste' problem is reaching proportions that are a cause for major concern (Fenniel and Marc, 2009; Laura *et al*, 2007; Ingwald and Gerold, 2004; Otoniel *et al*, 2001).

In Kano state, the 'cultural' practice of open air burning has been adopted by both urban and rural settlers in managing the waste that comes from agricultural sites, including cassia tora. This uncontrolled burning has a hazardous effect on the environment and if not carefully monitored can lead to bush burning and fire destruction. However, in a few instances the rural settlers utilise the dry stem of cassia tora as an energy source for domestic cooking.

Adopting an integrated waste management system can help in curtailing the problems associated with agricultural and municipal waste. The waste33

can be condensed into an energy commodity for domestic and industrial use. This will aid environmental protection and economic optimization.

1.3 Aim

The aim of this project is to investigate the production of fuel pellets from cassia tora stems under different temperature and pressure conditions for domestic and cottage industry applications and assess its economic viability for these applications.

1.4 Objectives

1. Conduct laboratory-scale production of the cassia tora stem pellets under varying production conditions and, determination of the physical properties, proximate and ultimate analyses of the fuel pellets produced.

2. Investigating the variation in production conditions of compression and temperature on the physical and chemical properties of the pellets before and after six month storage.

3. Determination of the kinetic parameters of the produced pellet.

5. Evaluation of the cost of production of the fuel pellets for conditions found in Kano state, Nigeria.

6. Evaluation of households' willingness to pay using contingent valuation method (CVM) for the fuel pellets produced.

1.5 Significance of the study

Provision of new knowledge and understanding on:

- the cassia tora stems pellets' characteristics and energy potential, to guide in accurately building and running combustion systems;
- meeting world environmental regulations and countering the negative effects associated with the current rate of deforestation for fuel wood consumption by evaluating cassia tora as an alternative energy source;
- the properties of stored cassia tora fuel pellets with respect to their preservation as an energy source;
- the economics of converting cassia tora stems into energy material to aid Nigeria's' progress towards promoting industrial growth and jobs alongside a better environment.

1.6 Methodology

The methodology that was used in carrying out the research work included the following:

a) a critical literature review;
b) laboratory scale production involving mould fabrication, material preparation, production, storage and characterization of the pellets measured by standards organisations including the technical committee developing the draft standard to describe all forms of solid biofuels within

Europe (CEN/TC 335), Austrian standard (ONORM), German standard (DIN), and American Society of Agricultural and Biological Engineers (ASABE).

c) determination of the physical characteristics of the fuel pellets, i.e. pellet dimensions, bulk density, particle density, durability and compressive strength according to CEN/TS 14588: 2005, CEN/TS- 15103: 2009, CEN/TS 15150: 2006, BS EN-15210-1: 2009 and ASABE (S368.4) respectively.

d) gross calorific values of the fuel pellets determined according to the BS EN 14918: 2009 standard using a bomb calorimeter;

e) proximate analysis of the fuel pellets according to the CEN/TC 335 standard to determine the moisture, volatile matter, fixed carbon and ash content;

f) ultimate analysis conducted according to the CEN/TS 15104:2005 standard to determine the C, H, N, O, and S content;

g) elemental analysis to determine K, Cu, As, Zn, Cr, Pb and Cl (major concerns in combustion systems and the environment) according to the CEN/TS 15290/97 standard;

h) obtaining demand side information on household's valuation of the cassia tora fuel pellets as a possible substitute for other domestic energy fuel commodities in Kano state, by use of the contingent valuation technique; for this purpose, a structured contingent valuation (CV) questionnaire was administered to 420 randomly selected households from the 6 local government areas within the Kano metropolis; Chi-square analysis was used in the assessment of the significance of socio-economic and demographic characteristics on households' willingness to pay for the introduced cassia tora stem pellets.

1.7 Research scope

The scope of the research includes pellet production under varying temperatures and pressures conditions, determination of the physical and chemical properties of the fuel pellets produced, economic cost of production and households' acceptance and willingness to pay for the fuel pellets. The thesis is divided into 9 chapters, whose structure and content are given in Figure 1.1.

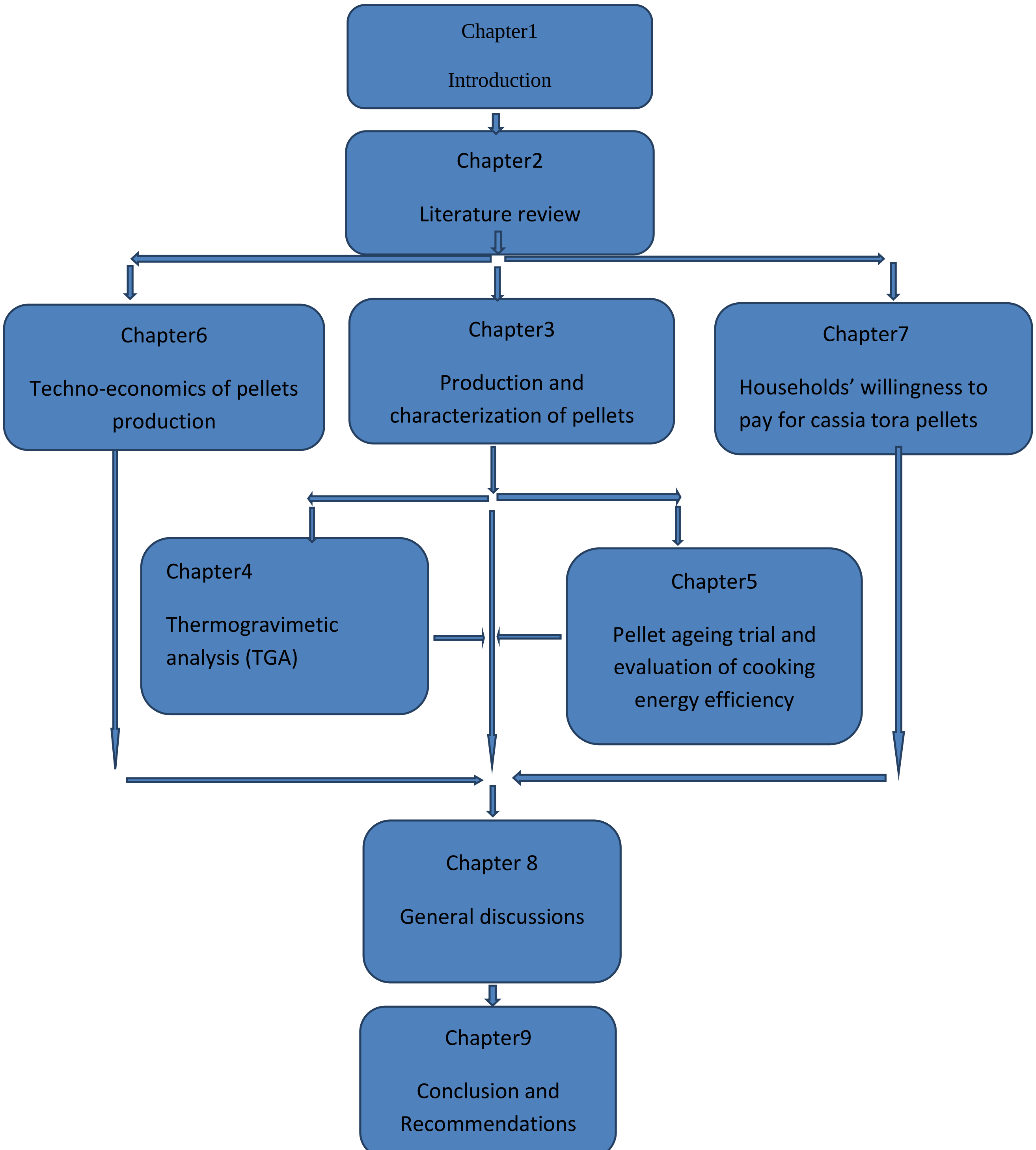

Figure 1.2: Structure and content of the thesis

Chapter 1: “Introduction” provides an overview about the research topic including aim and objectives with a brief summary of the content of each chapter.

Chapter 2: “Literature review” gives detailed information about production characterization and influence of production conditions on the properties of fuel pellets. It also provides a detailed review of research in fuel pellet production and characterisation. The review includes the effects of particle size, moisture, temperature and pressure on the density, compressive strength, durability, and calorific value; also the effect of storage on the properties of fuel pellets. This chapter also covers the contingent valuation technique (CVT) and its application in determining households’ willingness to pay for improved services or newly introduced commodities. Reviews on the application of CVT in determining households’ willingness to pay for improved waste collection services in Nigeria are also presented.

Chapter 3: “Production and characterisation of cassia tora stem pellets” provides the detailed description of materials, instruments and techniques used in the production and characterisation of cassia tora stem pellets. It gives information about particle size distribution, material/binder composition and material preparation.

Chapter 4: “Thermogravimetic analysis (TGA) and determination of kinetic parameters of the produced pellets’’ presents the kinetic information of the cassia tora pellets. Pellets produced at 120 MPa and 100ºC was used for the TGA. The analysis was carried out using a PerkinElmer Pyris 1 TGA, controlled using PerkinElmer Pyris thermal analysis software version 9.0.

Chapter 5: ‘’ Pellet ageing trial and evaluation of cooking energy efficiency’’ provides details of the investigation into effects of storage (six months) on the chemical properties of the pellets and also the evaluation of the cooking energy cost and efficiency as compared to fuel wood, LPG and kerosene.

Chapter 6: “Economics of producing fuel pellets from cassia tora stems” presents the techno-economics of producing cassia tora stem pellets for conditions found in Kano state, Nigeria. The capital, operating, personnel and total costs of production are discussed. A base case scenario of 5t/h cassia tora pellet production and operating over 210 days annually is assumed in the analysis. Costs associated with crop production, land, machine purchase (imported) and maintenance, offices, transportation and personnel are also considered in the analysis.

Chapter 7: “Households’ willingness to pay for cassia tora stem fuel pellets” involves an examination of the background of the study area, the population of the study, the sample size and sample technique, method of data collection and model adopted and techniques of estimation.

To obtain demand side information on household’s valuation of the cassia tora fuel pellets as a possible substitute for other domestic energy fuel commodities in Kano state, the contingent valuation technique was applied. For this purpose, the structured contingent valuation (CV) questionnaire was administered to 420 randomly selected households from the 6 local government areas within the Kano metropolis.

Chapter 8: In “General discussion” the results reported in Chapters 3, 4, 5 and 6 and the economics of cassia tora fuel pellet production in Kano state covered in Chapters 7 and 8 are discussed.

Chapter 9: In “Conclusions and Recommendations” the main conclusions and limitations of using cassia tora stem pellets as an energy fuel in Nigeria are given. Recommendations are made regarding policy making and investment in utilising agricultural solid waste/ residues for pellet production in Nigeria.

2. LITERATURE REVIEW

This literature review identifies previous work relevant to this study. This includes biomass densification, characterisation, pellet properties and influence of storage on pellets, and the economics of pellet production. Also reviewed are the economics of producing biomass pellets, valuation techniques and households' willingness to pay for a commodity, and issues on energy sources and their utilisation in Nigeria are briefly discussed.

The use of agricultural residues/waste in the making of pellets as a densified energy product could serve as a source of energy for domestic and cottage industries. It was highlighted in the Introduction to this study (Chapter 1) that, Nigeria is experiencing a problem of energy shortage, especially in the Northern part of the country. With the availability of a vast amount of agricultural residues/waste, that is not properly managed or utilised, converting these into densified products like fuel pellets could help in curtailing the energy crisis and cassia tora stems maybe be a good alternative for fuel pellet production in Nigeria. Biomass materials have a higher bulk density, better handling in transportation, storage and combustion equipment, when compacted into fuel pellets. The use of these pellets also offers a viable solution to the problems of deforestation and other environmental associated problems that result due to continued felling of trees in order to meet domestic and cottage industries' energy demands.

2.1 Biomass densification

Volume reduction (densification) is the term used to describe the process whereby initial volume occupied by a material is reduced usually, by the application of force or pressure (Jorelyn *et al*, 2008; Purohit *et al*, 2006; Yaman *et al*, 2000). It is a technique of conversion of solid waste into an energy commodity. The techniques employed are briquetting and pelleting.

Briquetting is the process of binding together pulverised carbonaceous matter in pressure moulds, often with aid of a binder (Purohit *et al*, 2006; Ni-Ben *et al*, 1999). The process of making briquettes is essentially a physical process which usually consists of crushing, screening, mixing with binder and pressing (Ni-Ben *et al*, 1999). Briquetting increases the strength, density, handling and transport qualities, and the amount of heat emitted per unit volume of biomass (Wolfgang *et al*, 2011; Yaman *et al*, 2000). The solid briquettes can be utilised immediately or can be stored for a relatively long period of time before use. When briquettes are gasified the resulting flue gases are of a sufficient high quality that they can be ignited and used to drive jet turbines for producing electricity and subsequently to create steam (Richard and Leaver, 2009). Although briquettes can be used as a source of heat for energy applications, the size of the briquettes limits their application, especially in automated, controlled combustion equipment and also they cannot be used directly in portable domestic stoves. Briquettes have to be crushed to the required size before intake into the combustion equipment process.

Pelleting is the process of compacting material into homogenous cylinder shape under controlled temperature and pressure, with or without the addition of a binding mechanism. Most of the fuel pellets currently produced come from the by-products of forest industries such as sawdust and wood shavings (Larsson and Rudolfsson, 2012). However, problems of shortages in supply and accessibility of forest industry by-products encourages the use of other raw materials which include agricultural by-products due to its high feed stock potentials for pellet production (Lar, 2005).

Industrial and laboratory scale production of biomass pellets have been reported (Eggerstedt and Wang 2014; Kong *et al*., 2012; Lehmann *et al*., 2012; Theerarattananoon *et al*., 2011; Zamorano *et al*. 2011; Gill *et al*. 2010; Adapa *et al.*, 2009; Chuen-Shii *et al* 2009; Miranda *et al.*, 2009; Bergstrom *et al.*, 2008; Andrejko and Grochowicz, 2007) where different equipment and raw materials were employed in order to investigate their energy characterisation, physical properties, durability, compaction characteristics and the pelletising process.

Chuen-Shii *et al* (2009) adopted a stainless steel mould to produce briquettes from rice straw and rice bran, varying the ratio of rice straw to rice bran mixture. They used a manual-operation hot press with a maximum capacity of compression of 100 kgf/cm^2 gauge pressure (9.8 MPa) and a maximum heating capability of 200^oC, and a rate of pressure increase of 8 $kgf/cm^2/min$ (0.785 MPa/min). The briquettes were produced at a pressure of 83.7 kgf/cm^2 (8.21 MPa) and temperatures of 90, 110, 130 and 150^oC. The upper and lower plates of the hot press were heated to a pre-set temperature via an electric heater and the temperature maintained for 10 min. For every production of the briquette the mould had to be assembled and fastened with a screw before placing it between the upper and lower plates of the hot press. This method makes it difficult to immediately eject the briquette for analysis since the temperature of the mould has to be lowered to room temperature before it were unscrewed and therefore time consuming. None the less the stainless steel mould could be modified for laboratory pellet production.

Gill *et al*. (2010) produced 8 mm diameter pellets from pine sawdust, chestnut sawdust, eucalyptus sawdust, cellulose residue, coffee husk and grape waste, in a TDP bench top press unit equipped with a single punch and die set, in order to evaluate the durability and combustion characteristics of the pellets. The raw materials were dried and ground before sieving to obtain a particle size fraction below 1 mm, of which some were mixed with 0.212 mm fraction of particle sizes of coal to produce biomass/biomass and biomass/coal blended pellets. The production temperature and pressure were not varied in the study and therefore no information of the effect of production condition on the produced pellets could be provided. The single punch die arrangement could be modified to form a dual or more plunger die with temperature control attached for better pellet production.

Laboratory scale pellet production was conducted by Eggerstedt and Wang (2014), to produce pellets from hard wood and switch grass in different proportions. With a particle size of less than 6 mm and an aluminum cube shaped mould with 5 chamber holes, and a sing a carver 3912 hot press with a maximum clamping force of 120 kN and a maximum temperature of 500ºC, a total of 45 different pellets were easily produced at 150ºC for 150 s under a pressure of 31 MPa. Although smaller samples of pellets were produced for analysis and there was low material wastage, and the method also allowed for ease of variance in the pelletising process parameters, it required the temperature controlled carver hot press, and this is a setback where the equipment is not available.

Fuel pellets have been proven to be an important energy commodity due to a large market in Europe and many other countries (Gilbert *et al*, 2009). This has made it significantly important for manufacturers to look into the quality of pellets they produce. With respect to use in automatic heating systems for the residential sector, a high quality pellet is required (Obernberger and Thek, 2004). According to Huang (2009) the requirement for a high-quality fuel pellet includes among others, abrasion resistance, low pollutant emission during combustion or gasification and a high calorific value. Standards are implemented in some countries according to specifications given by standard organisations (CEN/TC 335; ASTM; ASABE; ONORM; DIN) for high-quality fuel pellet production. The limiting values of the biomass pellet physical and chemical parameters defined by these standard organisations are used in the assessment of the qualities of pellets for transportation, storage and usage in domestic and industrial applications (Obernberger and Thek, 2004). The standards or technical specifications, and pellet parameters with their requirements are presented in tables 2.1 and 2.2. The specified methods of determination of the properties are treated in Chapter 3.

Table 2.1: List of standards or technical specifications to determine solid fuel properties

Property	Austrian specification ONORM[1]	European committee standardization CEN/TS[2]
Particle size distribution	Not published	CEN/TS 15149-2
Dimensions	ONORM M 7135	Not published
Bulk density	ONORM M 7135	CEN/TS 15103
Particle density	ONORM M 7135	CEN/TS 15150
Moisture content	ONORM G 1074	CEN/TS 14774-2
Ash content	ONORM G 1075	CEN/TS 14775
Durability	ONORM M 7135	CEN/TS 15210
C, H and N content	ONORM G 1071	CEN/TS 15104
Cl, Na and K content	Not published	To be published
S and Cl content	Not published	To be published
K, Cu, Zn, As, Cr, Pb and Cd content	Not published	To be published

1. Obernberger and Thek (2004)
2. CEN/TS 14961: E (2005)

Table 2.2: Specifications of properties of pellets (parameters and requirements)

Property	ORNOM specification[1]	CEN/TS specification[2]
Diameter D, length L (mm)	$D \leq 10$mm and $l < 5D$	$D \leq 12$mm +1.0 and $L \leq 4 \times D$
Moisture M	$M < 10\%$	$M \leq 15\%$
Ash A	$A < 5\%$	$A \leq 6\%$
Durability (Du_{90})	$Du \geq 97.7$	$Du \geq 90\%$
Additives	Not specified	To be stated by the manufacturer
Net calorific value	-	MJ/kg as received, to be stated by the retailer
Gross calorific value	18 MJ/kg	-
Bulk density kg/m^3		To be stated if traded by volume basis
Chlorine (Cl) (%wt)	< 0.02	$Cl \leq 0.1$
Sulphur (S) (%wt)	< 0.04	$S \leq 0.1$ if $S > 0.2$ actual value to be stated

1. Garcia et *al*., (2011)
2. CEN/TS 14961:E, (2005)

2.2 Characterisation of biomass pellets

The quality of a biomass pellet generally depends upon its chemical, mechanical and physical properties in terms of thermal utilisation (Kaliyan and Morey, 2009; Van Loo and Coppenjan, 2008; Obernberger and Thek, 2004). These properties are related to the type of raw material used in production (Arshadi *et al*., 2008; Rhen *et al*., 2005) and the quality management of the production process (Gilbert *et al*., 2009; Lehtikangas, 2001; Li and Liu, 2000).

Different biomass materials possess physical and chemical properties that differ from each other and that influence their properties as fuel pellets (Gil *et al.*, 2010). The quality management of the production process includes proper control of steam conditioning/preheating of feed, forming pressure, binder/additives and feed constituents mixing, pellet mill variables, densification equipment variables and post production conditions (Kaliyan and Morey, 2009).

The chemical properties of biomass pellets include calorific value, proportion of fixed carbon, and volatiles, and the physical and mechanical properties are particle density, bulk density, durability and compressive strength (Theerarattananoon *et al*., 2011Gil *et al*., 2010; Miranda *et al.*, 2009). Moisture content must also be taken into account with respect to properties.

There are three main analyses done to determine the chemical characteristics of a solid fuel, i.e. proximate and ultimate analyses, and determination of calorific value (gross (GCV) and net (NCV). The knowledge of this information helps in determining the energy potential of the fuel, efficiency of use, its price and proper design and operation of a thermal system (Akkaya, 2009; Morris, 1998). According to Ahmaruzzaman (2008), proximate and ultimate analyses are necessary for efficient and clean utilisation of the fuel, while the calorific value determination is to know the quantity of energy in the fuel.

Oberberger and Thek (2004) investigated the physical characterisation and chemical composition of densified biomass fuels and produced the results of the analysis of 21 wood pellet samples with average values of diameter, length, bulk density, particle density, water content, ash content, abrasion, starch content, GCV and NCV of 7.1 mm, 16.1 mm, 591 kg/m^3, 1.18 kg/dm^3, 7.7 wt % (w.b.), 0.51 % (d.b.), 4.05 % (w.b.), 0.22 wt % (d.b.), 20.3 MJ/kg and 19.0 MJ/kg, respectively. They also reported the average values of the elemental analysis to be, for C, H and N, 50.03, 5.7 and 0.22 wt % (d.b), respectively and for, 278, 48, 493, 0.14, 0.43, 13.2, 0.6 and 1.1 mg/kg (d.b.) for S, Cl, K, Cd, Pb, Zn, Cr and Cu. They also reported the analysis of straw pellets with average values of diameter, length, bulk density, particle density, water content, ash content, abrasion, starch content, GCV and NCV of 8.1 mm, 16.6 mm, 660 kg/m^3, 1.08 kg/dm^3, 7.2 % (w.b), 5.97 % (d.b.), 2.37 wt % (w.b), 18.6 MJ/kg, 17.4 MJ/kg, with 46.1 wt % (d.b.), 5.4 wt % (w.b.) and 0.55 wt % (d.b.), and 745, 1158, 8680, 0.11, 0.71, 10.0, 2.3, and 2.8 mg/kg (d.b.) for C, H and N, and S, Cl, K, Cd, Pb, Zn, Cr and Cu respectively. The summary of the properties of solid fuels from the literature, the values determined by the researcher is compared with the solid biofuels specification of CEN/TS 14961:2005 and presented in table 2.3. Although the analysis was carried out according to guidelines by standard organisations, the pellets involved in the analysis were produced in different plants, on different pellet mills and with different densification technologies, under different conditions and from different biomass.

The energetic characterisation of densified residues from Pyrenean oak forests was reported by Miranda et al.(2009), where pellets were produced from 3 different branch sizes of the plant material and 8.37, 5.58 and 6.32 wt % wet basis of moisture, 79.31, 80.54 and 81.51 wt % dry basis of volatile, 3.32, 2.81 and 2.40 wt % dry basis of ash, 17.37, 16.65, 16.09 wt % dry basis of fixed carbon, 50.15, 48.88 and 51.20 wt % dry basis of C, 6.10, 6.14 and 6.37 wt % dry basis of H, 1.47, 1.24 and 1.89 wt % dry basis of N and <0.1, 0.1 and 0.1 wt % dry basis of S for smaller, medium and larger branches respectively. They concluded that the analysed properties of the pellets vary depending on the changes in the branch diameter of the tree but the variability was not considered very significant. The CEN/TS 335 standard method was employed in the analysis but variability in pellet qualities with respect to different branches of the same biomass material is seldom reported in the literature and so it could not be generalised for all materials.

Table 2.3: Summary of physical and chemical properties of pellets from literature compared with the researcher's determined values.

Parameter	Unit	Wood pellets samples average value[1]	Straw pellets[1]	Researched value[2]	CENT/TS guiding values[3]
Diameter	Mm	7.1	8.1	14.0	D≤12mm+1mm
Length	Mm	16.1	16.6	43.7	L≤ 4xD
Bulk density	kg/m3	591	660	619.20	-
Particle density	kg/dm3	1.18	1.08	1.75	-
Moisture content	wt% (w.b.)	7.7	7.2		M≤ 10% as received
Ash content	wt% (d.b)	.51	5.97		A≤6% (d.b)
Durability	% (d.b.)	95.95	97.3		Du ≥90.0%
GCV	MJ/kg	20.3	18.6		-
C	wt% (d.b)	50.03	46.1	41.5	-
H	wt% (d.b)	5.7	5.4	5.49	-
N	wt% (d.b)	.22	.55	1.48	N≤3%
S	wt% (d.b)	278	745	210	S≤0.1
Cl	mg/kg (d.b)	48	1158	56	Cl≤0.1%
K	mg/kg (d.b)	493	8680	390	-
Cd	mg/kg (d.b)	.14	.11	.13	-
Pb	mg/kg (d.b)	.43	.71	.13	-
Zn	mg/kg (d.b)	13.2	10.0	3.0	-
Cr	mg/kg (d.b)	.6	2.3	1.0	-
Cu	mg/kg (d.b)	1.1	2.8	.5	-

1. Obernberger and Thek (2004)
2. Values determined by the researcher.
3. CEN/TS 14961: E, (2005)

2.2.1 Proximate analysis

Proximate analysis gives the moisture, volatile matter, fixed carbon and ash content of a particular solid fuel (Erol *et al*, 2010) and it is the easiest and the most widely used method to characterise a biomass fuel (Changdong *et al*., 2005). The moisture content varies depending on the type of biomass. Most agricultural residues have low moisture contents, varying from 7.4 to16.8 % for corn straw and mint straw, respectively (Vassilev et al, 2010). Few residues have very high moisture content, as seen in the case of bagasse with about 40-60 % (Clarke, 1988). The Proximate analysis data is obtained easily using common equipment (Majunder *et al*, 2008) or calculated using correlations (Junfang *et al*., 2010).

Junfang *et al*., (2010) developed a correlation with effect of ash taken into account and using data points selected from different categories of biomass and suggested the correlation for the ultimate analysis can be used to compute the elemental analysis of biomass accurately such that;

$$C = 0.635\,Fc + 0.460\,Vm - 0.095\text{ ash} \qquad 2.1$$

$$H = 0.059\,Fc + 0.060\,Vm + 0.01\text{ Ash} \qquad 2.2$$

$$O = 0.340\,Fc + 0.469\,Vm - 0.023\text{ Ash.} \qquad 2.3$$

Where, *Fc*, *Vm* and ash are the percentage of fixed carbon, volatile matter and ash in the fuel respectively. The correlations from the literature were used to determine the proximate analysis values for cassia tora and the result compared with that experimentally determined, and this is presented in table 2.4.

Table 2.4: Gross calorific values calculated using models and experimentally determined value

GCV from literature[1] MJ/kg	GVC from literature[2] MJ/kg	Experimental GCV[1] MJ/kg
16.40	27.06	17.89
7.25	27.39	17.89
17.46	27.47	17.95
16.71	27.27	18.09
16.95	27.41	17.89
17.51	27.71	18.08
17.81	28.34	18.09
16.78	28.73	18.09
17.27	27.51	17.89
17.78	28.04	18.09
17.78	28.69	18.09
17.78	28.69	18.1

1. Jigishi *et al*, (2005)
2. Majunder *et al*, (2008)
3. Determined by the researcher.

Mayerol et al., (2001) conducted an experimental optimisation by a simple method of proximate analysis of coal and biomass by thermogravimetic analysis (TGA), using heating rate, final temperature, holding time, air flow and sample size as control variables. The relative accuracy of the method was demonstrated by determination of the volatile matter contents of a number of coals in parallel with ASTM certified methods. It was found out that the method was only successful with biomass samples and cannot be generalised for all solid fuels.

Gil *et al*. (2010) reported proximate and ultimate analyses of pellets from biomass blends with the results in the range of 45.2 – 50.0 % C, 6.0 – 6.3 % H, 0.1 – 2.6 % N, 51.0 – 34.4 % O, 0.0 – 0.2 5 % S, and 0.2 – 4.5 % ash, 13.35 – 16.1 % fixed carbon (FC), 67.9 – 86.3 % volatile (VM) and 17.6 – 22.1 MJ/kg, for different selected biomass raw materials. Similar results were obtained by Zamorano et al (2011) with pelletised agricultural residues.

The standard laboratory methods of determination of proximate analysis are given in CEN/TC 335 and DIN standards as reported by Zamorano *et al*. (2011) and Obernberger *et al*. (2004).

2.2.2 Influence of moisture, ash and volatile content on pellet quality

Moisture content is influential in the combustion process of biomass fuels by increasing the volume of the flue gas produced per energy unit of the fuel (Demirbas, 2004). Biomass materials having a high moisture content have the tendency not to react spontaneously during combustion and this reduces the combustion temperatures and increases the time taken for it to completely combust in combustion chamber (Hellwig, 1985; Jenkins et al., 1998; Obernberger and Thek, 2004; Demirbas, 2005; Van Loo and Koppenjan, 2008).

Moisture content in wood was found to affect the performance in water boiling; time to boil the water, specific fuel consumption and energy efficiency (Yuntenwi et al., 2008). They observed that too much moisture resulted in longer time to boil the water, increased emission and fuel use.

The volatile matter of a solid fuel is a measure of the ease with which the fuel can be ignited and subsequently gasify or oxidise, and is defined as the proportion of the fuel driven-off as gas, which includes the moisture, by heating to 950^{o}C for 7 minutes (McKendry, 2002). Volatile matter includes, light hydrocarbons, carbon monoxide, carbon dioxide, hydrogen, moisture and tars.

Biomass materials have a high content of volatile matter (Van Loo and Koppejan, 2008) making them easy to ignite at relatively low temperatures. Biomass fuels usually have a volatile matter varying between 76 to 86 % (Van loo and Koppejan 2002), associate with rapid and difficult to control in combustion (Weather et al., 2000) and where a complete combustion with high efficiency with low emission require burning in high temperature zone for a long period of time (Khan *et al*., 2009). Ash is the organic incombustible part of fuel that is left after complete combustion and constitutes the bulk of the mineral fraction of the original biomass (Khan *et al.,* 2009). Ash content affects the heating value of fuel, where the higher the amount of ash the lower is the heating value (Khan *et al*., 2009).

2.2.3 Calorific value

The energy content of a fuel is measured by its calorific value (CV), which is the energy released when the fuel is burnt and represents the difference between the chemical energy of the fuel and oxygen and the chemical energy of carbon dioxide and water (Yin, 2011; Larkin et al., 2004; Jenkins *et al*., 1998). The gross calorific value (GCV) in Joules per kilogram (J/kg) is the total energy content released when a fuel is burnt in air, and it includes the heat of condensation of water in the combustion products, while the net calorific value (NCV) is defined as the amount of heat released by combusting a specified quantity of fuel initially at 25^{o}C and returning the temperature of the combustion products to 150^{o}C following combustion (Eastop and McConkey, 2004). A bomb calorimeter is employed in the measurement of calorific values of solid fuels.

The calorific value of biomass fuel can be determined experimentally or calculated from the ultimate and/ or proximate analysis results (Haykiri-Acma *et al*., 2006; Parikh *et al*., 2005; Sheng and Azevedo, 2005). Jigisha *et al*., (2005) developed a correlation for calculating calorific values (higher heating values, HHV) from proximate analysis of solid fuels, and they established a relationship that,

$$HHV = 0.356Fc + 0.1559Vm - 0.0078\ Ash \qquad 2.4$$

Where, *Fc*, *Vm* and ash are the percentage of fixed carbon, volatile matter and ash respectively for biomass fuel pellets.

Changdong and Azevedo, (2005) developed a correlation to estimate gross calorific value of biomass fuels from basic data and found out that the correlations based on ultimate analysis were most accurate, while that based on biochemical composition of the fuel were not to be relied on. Also Majumder *et al*., (2008) developed another new proximate analysis based correlation to predict calorific values of coal with 250 samples of coal. The correlation was given as;

$$HHV = -0.03\,(A) - 0.11(M) + 0.33\,(Vm) + 0.35\,(Fc) \qquad 2.5$$

Where, *A, M, Vm* and *Fc* are the percentage of ash, moisture, volatile matter and fixed carbon respectively.

On the other hand Miranda *et al.* (2009) experimentally determined the HHV of Pyrenean oak ‘chips’ from small, medium and large branches, obtaining 19.20, 19.24 and 19.17 MJ/kg respectively. When compared with values of HHV determined for pellets made from the small, medium and large branches, they obtained 19.44, 19.19 and 19.30 MJ/kg, respectively; thus HHV increased marginally when the chips were pelletised. Zamorano et al. (2011) and Obernberger and Thek (2004) obtained similar results experimentally for different material pellets. Pellets made from almond tree, black poplars, olive tree, holm oak and olive tree materials were experimentally investigated to have 4308 (18.05), 4428 (18.56), 4496 (18.84), 4411 (18.48) and 4438 (18.60) kcal/kg (MJ/kg) HHV respectively. And Obernberger and Thek (2004) determined the HHV for straw pellets to be 18.6 MJ/kg while for that of wood bark pellets it was 20.3 MJ/kg.

2.2.4 Ultimate analysis

Ultimate analysis data gives the composition of the fuel in weight percentage (wt %) of carbon, hydrogen, oxygen, sulphur and nitrogen (Ahmaruzzaman, 2008). Near infrared spectroscopy (NIRS) is a method employed in utilising the near-infrared region of the electromagnetic spectrum for the determination of ultimate analysis (Erol *et al*, 2010). Gil *et al*. (2010) reported proximate and ultimate analyses of pellets from biomass blends with results in the range of 45.2 – 50.0 % C, 6.0 – 6.3 % H, 0.1 – 2.6 % N, 51.0 – 34.4 % O, 0.0 – 0.2 5 % S, and 0.2 – 4.5 % ash, 13.35 – 16.1 % fixed carbon (FC), 67.9 – 86.3 % volatile (VM) and 17.6 – 22.1 MJ/kg (GCV) for different selected biomass raw materials.

Although some researchers use correlation as a short cut to the determination of proximate and ultimate analyses, and calorific value of biomass solid fuel, the experimental method is the best option, as per the provision of standards organisations (CEN/TC 335), for obtaining a better knowledge of the heating value of a particular biomass fuel.

2.2.5 Pellet dimensions

The importance of dimension in pellets is mainly in the ratio of length to diameter, which is relevant if pneumatic feeding systems are used (Obernberger and Thek, 2004), due to the fact that longer pellets are able to block transport pipe of such systems.

2.2.6 Density

This is the mass per unit volume of the fuel that is used to assess the compression quality in terms of a single product (particle density) or large volumes (bulk density) (Carrie *et al*., 1987; Smith *et al*., 1977). Particle density is important in the sizing and handling of combustion feed systems (McKendry, 2002), while bulk density directly affects the efficiency in transportation and storage of biomass fuels (Lehtikangas, 2001; 2000). The higher the particle and bulk densities the better handling in combustion, the lower the transportation cost and storage capacity (Obernberger and Thek, 2004)

2.2.7 Durability

A minimal amount of fines is required for proper operation of combustion equipment. A high percentage of fines amounts to an increase in dust, causing risk of dust explosions, increased storage temperature and health problems that can occur in inhalation during handling (Obernberger and Thek, 2004; Lehtikangas, 2000). High durability ranges from 80 -100 %, medium 70 – 80 % and low 70 % and below (Tabil and Sokhansanj, 1996).

2.2.8 Compressive strength

The compressive strength is the maximum crushing load that a pellet can withstand before breaking when it is placed between two flat metal plates (Kaliyan and Morey, 2006; CEN/TC 335). It is a good quality of fuel in relation to compressive strength during storage (Tabil et al 1997). Compressive force of beech, spruce and straw pellets at 20 and 100^{o}C production temperatures were reported to be 0.93 and 1.53, 1.09 and 1.27 and 0.24 and 0.37 kN respectively (Stelte *et al*., 2011).

Bergstrom et al (2008) in their work, measured the compressive strength of scots pine sawdust pellets to be 61.2, 51.3 and 40.1 N/mm^2 /mm for fine (<1 mm), medium1.0<2.0 mm) and coarse (2<4.0 mm) raw material particle sizes respectively. They eliminated the need of end-cutting of the pellets to equal length which could have affect the pellet durability.

2.3 Influence of process parameters on the properties of fuel pellets

2.3.1 Role of lignin and biomass pellet production

Lignin is an organic substance which found to bond the cells, fibers and vessels which constitute wood and the liquefied elements of plants as it is observed in straws (ww.lignin.com/aboutlignin.php).

In biomass pellet production lignin contributes to self- bonding of woody particles during pelletisation. Thermal pretreatment enhances the flow of lignin in the form of liquid (lignin liquid intermediates, LLI) from the cell wall and middle lamella, and deposits on the fiber surfaces in or outside the secondary cell wall. This plays an important role on bonding particles during pelletisation as well as wood composites (Palaez *et al.*, 2014).

2.3.2 Adhesion and cohesion forces

Defined as the tendency of dissimilar or identical particles or surfaces respectively, to cleave together is nevertheless influenced by lignin content, temperature, binder addition and availability of moisture in the form of steam (Israel, 1985). The forces that cause adhesion and cohesion are categorized into chemical, dispersion and diffusive.

Chemical adhesion is the phenomenon where two materials may form a compound at the join. The strongest joints are where atoms of the two materials swap or share electrons is known as ionic bonding or covalent bonding, respectively. However a weaker bond is formed if a Hydrogen atom in one molecule is attracted to an atom of nitrogen, oxygen, or fluorine in another molecule, a phenomenon called hydrogen bonding. On the other hand chemical adhesion occurs when the surface atoms of two separate surfaces form ionic, covalent, or hydrogen bonds. Thus if surface molecules can bond, then the surfaces will be bonded together by a network of these bonds. And therefore in general not only that surfaces with the potential for chemical bonding need to be brought very close together, but also that these bonds are fairly brittle, since the surfaces then need to be kept close together (Salez et al., 2013).

In dispersive adhesion two materials are held together by van der Waals forces in which is the attraction between two molecules, each of which has a region of slight positive and negative charge.

In ectrostatic adhesion, some conducting materials may pass electrons to form a difference in electrical charge at the join. This results in a structure similar to a capacitor and creates an attractive electrostatic force between the materials. Diffusive adhesion refers to a situation when some materials may merge at the joint by diffusion. This may occur when the molecules of both materials are mobile and soluble in each other. This would be particularly effective with polymer chains where one end of the molecule diffuses into the other material. It is also the mechanism involved in sintering (Kendall, 1994).

In addition to the cumulative magnitudes of these intermolecular forces, there are certain emergent mechanical effects. The ability of the particles to cleave together requires certain amount of energy that can come from chemical (as in binder addition with or without heat treatment) and / or physical linkages like pressure and temperature processes (Maeda *et al.*, 2002). Understanding this requires the knowledge of the concept of surface free energy as described by Young-Dupré equation.

2.3.3 Young-Dupré theory of surface energy

Surface energy is defined as the work that is required to build a unit area of a particular surface of a substance. Relatively the surface energy is the work required to cleave a bulk sample, creating two surfaces. If the new surfaces are identical, the surface energy γ of each surface is equal to half the work of cleavage W, hence;

$$\gamma = (1/2)\, W11 \qquad 2.6$$

If the surfaces are unequal, the Young-Dupré equation applies and thus:

$$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12} \qquad 2.7$$

Where, γ_1 and γ_2 are the surface energies of the two new surfaces, and γ_{12} is the interfacial tension.

This methodology can also be used to discuss cleavage that happens in another medium where;

$$\gamma_{12} = (1/2)\ W121 = (1/2)\ W212 \qquad 2.8$$

These two energy quantities refer to the energy that is needed to cleave one species into two pieces while it is contained in a medium of the other species as the case with addition of an external medium like binder in pellet production (Maeda *et al*., 2002; Majmuder and Ghatak, 2007).

A basic understanding of the terminology of cleavage energy, surface energy, and surface tension is very helpful for understanding the physical state and the events that happen at a given surface. It is worth noting that there is no Grand Unified Theory of Adhesion. Therefore particular mechanisms are specific to particular material scenarios.

2.3.4 Influence of temperature

Carone *et al.,* (2011) investigated the influence of process parameters and biomass characteristics on durability of pellets from the pruning residue of Olea Europe L using three different biomass grinds of 1, 2 and 4 mm and conditioned at 5, 10, 15 and 20 % wet base (w.b), pelletised at 60, 90, 120 and 150^{o}C, with pressures of 71, 106, 141 and 176 MPa. They found out that a change in production temperature significantly affects mechanical properties more than the initial moisture content and the particle size of the raw material. Therefore good-quality pellets were produced with a high-temperature process, low moisture and reduced particle size.

Kaliyan and Morey, (2009) studied the factors affecting the strength and durability of densified biomass product and saw that the preheating condition affects the density and durability of densified products, such as pellets and briquettes. They noted that preheating at 65-100^{o}C produces high quality in terms of durability of densified products for a variety of biomass feed stocks.

The densification characteristics of corn cobs were investigated by Kaliyan and Morey (2010) and it was observed that at room temperature (25^{o}C) corn cobs with a relaxed density of 604 to 971 kgm^{-3} can be produced at a compression pressure of 150 MPa and geometric mean particle diameter of 0.85 to 2.81 mm. Kaliyan and Morey (2010) observed that the durability of corn cob briquettes made at room temperature was zero percent. But with a preheating temperature of 85^{o}C, a relaxed density of 1100 to 1120 kgm^{-3} and a pressure of 150 MPa the durability of briquettes produced was 88.2 % to 92.3 %.

2.3.5 Moisture addition (steam conditioning)

Fasina and Sokhansanj (1996) observed that moisture initially affected the durability of alfalfa grass pellets, but a further increase reduced the durability. According to Fasina, (2008) an increase in moisture decreases bulk density and particle density but increases pellet diameter. Therarattananoon *et al*., (2011) investigated the physical properties of pellets from sorghum stalk, corn stover, wheat straw and big bluestem. Wheat straw had the highest bulk density at 495.8 kgm^{-3} with sorghum straw having the least at 365.2 kgm^{-3}. Moisture can affect durability and bulk density such that an increase in the moisture content reduces the durability, bulk and particle density. They also observed that lower particle size increased bulk density. The optimal moisture conditions for alfalfa grass pellets reported by Tabil, (1996) were 8.5 to 10 %.

2.3.6 Influence of particle size distribution

Particle size of biomass raw materials has an influence on the quality of pellets. Better quality pellets with less densification energy are obtained with smaller particle sizes of raw materials. Bergstron *et al.* (2008) studied the influence of raw material particle size distribution on the pelletising process and physical and thermochemical characteristics of sawdust, and scot pines pellets. They observed that, particle size of 8 mm produced good pellets and a further reduction in particle size did not, however, change the quality of the pellets. Application of pressure by the densification equipment to the fed particles contributes to inter-particle bonding. High pressure squeezes out the natural binding components in the biomass material thus enabling different binding mechanisms. In the laboratory, pressure is studied using a closed-end die and piston assembly (Kaliyan and Morey, 2009), where pressure is applied on the powder mass by a universal testing machine or hydraulic press. The effect of pelletising pressure was observed by Wolfgang *et al*., (2011), investigating pelletising pressure and its dependency on production conditions, they concluded that pressure increases exponentially with pellet length, and also it influences pellet quality as density increases with an increase in pressure. However, when they increased the pressure to 200 MPa the increase in density of the pellets was minor. Srivastava *et al.* (1981) found that a pressure increase from 5 to 44 MPa increased the durability rating of grass hay mixed with alfalfa (20 %) from 5 to 91 %. An increase in the durability of rice husk briquettes (made from a particle size of 4.05 mm) from 80 to 95 % was reported by Singh and Kashyap (1985) when pressure was increased from 7.8 to 31.2 MPa. The densification behaviors of oak sawdust, oak mulch, oak bark, oak chips, pine sawdust, cottonwood sawdust and cottonwood mulch were studied by Li and Liu (2000) in the pressure range of 34 to 138 MPa. They found that increased abrasion resistance, impact resistance and compressive resistance resulted from increasing the densification pressure.

3.3.7 Binder addition

The lack of a binding component in biomass densification can result in poorly formed pellets that are dusty and difficult to handle in transportation and combustion equipment (Arshadi *et al.*, 2010). Natural binders in biomass materials are enhanced through preheating. This modifies the structure of the cellulose-hemicellulose-lignin matrix (Arshadi *et al.*, 2008) and improves the compression and compaction characteristics (ONORM M 7135, 2002). Activation of lignin and changes in the cellulosic structure during a steam explosion process facilitates the formation of new bonds (SS 187120 Biofuels and peat, 1998). Some materials cannot naturally form quality pellets without the addition of an external binder Lehmann *et al.*, (2012). Selection of binders largely depends on the cost and eco-friendly nature of the binder (Marrero, 1999; Tabil, 1996). Organic and inorganic binders have been employed in pellet industries for densification (Pietsch, 2002). Some binders are employed in order to improve the strength and durability qualities of pellets to match quality standards or marketing requirements (Tabil, 1996).

Dobie (1975) showed that hay could not be formed into quality densified cubes without the application of a binder. Addition of a binder at 5 to 10 % by weight increased the durability of the cubes from 93 to 97 %. Addition of about 5 % by weight of the binder to bagasse pitch increased the durability of the cubes from 88.8 % to 99.3 %.

Singh and Singh (1982) showed that addition of 10 to 25 % binder by weight of molasses or sodium silicate to rice straw enabled briquettes to be produced with 40 to 80 % durability, at a particle size of 0.15 mm and a production pressure of 29.4 MPa.

Tabil *et al.,* (1997) categorized the quality of alfalfa chops based on the durability of pellets obtained without addition of a binder. Quality was ranked high for a durability of more than 80%, medium between 70 and 80 % and low for less than 70 %. The durability and hardness of low quality alfalfa chops was improved by the addition of 0.2 % of collagen protein, 1.25 % of lignosulfonate, 5.0 % of bentonite, 1.9 % of hydrated lime and 0.74 % of pea starch, by weight respectively.

Gum Arabic as a binder has a high water solubility, low solution viscosity and is a low interfacial activity material (Ali *et al*., 2010). These properties have made gum Arabic very useful in many applications (Ayuni *et al.*, 2013; Chabot *et al*., 2013; Evans and Oloyede, 2011; ARMET-TR, 2010; Singh *et al.*, 2010). Ayuni *et al* (2013) studied the use of gum Arabic as a binder in preparation of starch based edible plastic. They concluded that the starch based edible plastic was successfully prepared using a mixture of gum Arabic and glucose.

2.4 kinetic parameters

Kinetic information is very important in the design, development and modelling of technologies based on the pyrolysis and combustion of lignocellulose materials (Ella *et al*., 2005).

The kinetic parameters determined in the pyrolytic characterisation of biomass are the activation energy (*Ea*), the reactivity (*A*) and the order of the reaction (Schniewind, 1989). Activation energy is a term introduced in 1889 by a Swedish scientist called Svante Arrhenius. It is defined as the energy that must be overcome in order for a chemical reaction to occur. It may also be defined as the minimum energy required to start a chemical reaction. The activation energy of a reaction is usually denoted by *Ea* and given in units of kilojoules/mole.

Activation energy is the dominating factor in the reactivity equation when thermal analysis results are concerned (Ella *et al*., 2004). The activation energy typically affects the temperature sensitivity of the reaction rate while the reactivity is related more with material structure. Thus the reactivity of biomass material is characterised by its activation energy. Generally, determination of these kinetic parameters depends on experimental conditions such as heating rate, sample size, moisture content of the sample and the heating medium (Nugroho *et al.*, 1998). Thermogravimetic (TGA) data is used in the determination of biomass kinetic parameters (Celyn and Topcu, 2014; Ibrahim *et al*., 2013; Pathasarathy *et al*., 2013; Polat *et al*., 2013; Yorulmaz and Atimtay, 2009; Mansaray and Ghaly, 1999). Quantitative methods are applied to TGA curves to obtain the kinetic parameters (Pathasarathy *et al.*, 2013).

2.5 Storage

Stored biomass fuels can have a reduced heating value due to microbial growth resulting in a deteriorated quality of the fuels and a temperature increase in the storage pile White and DeLuka (1978). Optimal temperature span for most micro-organisms acting on stored biomass materials is between 20 and 40^{o}C, while mould fungus can tolerate temperatures up to 70^{o}C during shorter storage time periods (Santamarta, 2011)

It has been shown (Jirjis and Theander, 1990) that oxidation processes are faster in biomass material containing a higher amount of lignin. Research by Thornquist (1987) made on biomass wood material reported the main factors influencing the increase in temperature in a stored stack to be moisture content, size of the pile and density. Lehtikangas (1998) practically proffers suggestions with regards to storage of biomass. This includes;

i. Biomass fuels should be dry (≤ 20 % moisture) before storage to avoid microbial growth.
ii. Avoiding mixing qualities among the fuels in storage
iii. Storage of fuels should be in small piles and during a short time.
iv. Metal objects should be avoided in piles.
v. Stored materials should be built in large elongated stacks with a base width of twice the height of the stack.

Research on the influence of storage conditions have been mostly concerned about the moisture content, which is a key to the microbial activities in biomass fuel storage. An increase in moisture content by more than 3 to 5 % due to storage under a high relative humidity of 70 to 90 % was reported to have a detrimental effect on the durability of alfalfa pellets (Fasina and Sokhansanj, 1996). Tabil (1996) studied the effect of high humidity storage in alfalfa pellet's durability and hardness. He also found out that an increase in moisture affected the durability and strength of the pellets, just as observed by Fasian and Sokhansanj (1996). The combined effect of temperature and relative humidity on the physical qualities of alfalfa cubes was studied by Khoshtaghaza *et al.* (1999). They found out that durability decreases as temperature and relative humidity increased. There was no effect on durability at low temperature and relative humidity levels (55 to 66 %). At temperature of 31.3°C and relative humidity of 80 % durability decreased from 90 to 50 % after 66 days of storage.

2.6 Cost of pellet production

Despite the increase in pellet production in most countries, it is difficult to obtain reliable information from the research community relative to production cost, requirements and market trends for biomass pellets. Generally, production costs can be seen to be affected by feedstock price, plant capacity and plant utilisation. The greater the plant's production capacity (t/hr) and hours of operation and the lower the feedstock cost ($/hr, €/hr or £/hr), the lower the production cost per metric ton of pellets (Obernberger and Thek, 2004; Garstang, 2001; William and Lynch, 1995; Urbanowski, 1984).

Pirraglia *et al.* (2010) developed a techno-economic model for the determination of production cost for the United States of America manufacturers based on a comprehensive investigation. An estimated cost of $ 12,240,000 total equipment and installation cost for 75,000 t/year and $ 6,584,000 operation cost per year was estimated using the model. They concluded that pellet production is profitable for U.S. manufacturers and distributor/retailers, with more margin for retailers.

Anthony *et al*. (2010) worked on the economic analysis of the manufacturing cost of pellet production in the Republic of Ireland using non-woody biomass.

With a case scenario of 6 t/hr., 8 t/hr. and 10 t/hr., the capital and operating cost were estimated. For the case scenario of eight t/hr the production cost was € 102/t of pellet and increasing the production capacity decreased the cost of production. They also found out that the cost of raw materials was about 66 % of the total pellet production cost while grinding, cooling and personnel were 10 %, 11 % and 9 % respectively. In their conclusion, they opined that pellets compete favourably with oil and gas and found the production to be economically viable.

Research by McKendry (2002) on energy production from biomass brought into light the cost of producing pellets from cereal straw, short rotation coppice and miscanthus to be € 45/t, € 75/t and € 86/t of dry matter respectively.

Mani *et al*. (2006) estimated pellet production cost of 51/t, capital costs of $ 6/t and an operating cost of $ 45/t. This estimation was based on drying the biomass used for pellet production. When drying is not required the pellet production cost decreases to $ 29.68/t. On the other hand, Styles *et al*. (2005) did the economic comparison of willow and miscanthus production with conventional farming systems for pellet production in Ireland. The cost of producing willow was estimated to be €31-46 and miscanthus € 37-48 per metric ton dry basis. Perlack and Turholloe (2003) did a feedstock analysis of corn stover residues for further processing, evaluating the cost of collecting, handling and hauling to an ethanol conversion facility. It was collected, stored and hauled for about $ 43.1-51.6/dry metric ton, using conventional bailing equipment for conversion facilities from 500-4000 dry t /day.

Literature on economics of pellet production is scanty and where available most reports are based on the economic conditions of a particular country and the availability of equipment and feed stock materials in the pellet production.

2.6.1 Willingness to pay concept and contingent valuation technique

Willingness to pay (WTP) is an important concept in environmental economics. It is one method that can be used to determine the price of goods, especially where price is not known. Therefore, it is a concept according to Philcox (2007) that defines the amount (measured in goods, services or dollars) an individual is willing to give up for a particular good or service. In economics, WTP represents one of the major alternative means to measure value, and today it is increasingly becoming popular as one of the standard approaches that are used by economists to place a value on goods or services for which no market-based pricing mechanism exists (Samwell *et al.*, 2012).

According to Jesdpipat (2003) WTP is the foundation of the economic theory of value. The idea is, if something is worth having, then it is worth paying for. In theory, according to Dixon (2008) economic value of any good or service is measured in terms of what people are WTP for the commodity less what it costs to supply it. Empirical studies have shown that WTP when conducted correctly is capable of providing an accurate result for true consumer demand of a public good (Samuelson, 1954; Bohm, 1979; Breidert, 2005; Mubyazi *et al* 2011).

An economy usually provides a mix of marketed and non-marketed goods; environmental goods come under the category of non-marketed goods. For many environmental goods, there are no markets for trading them due to their common property nature. This presents, of course, the problem of finding a market value for these non-market goods. Clearly, in the absence of market special techniques are needed to place consumers' preferences for environmental goods and services on common ground with demand for more conventional commodities (Kuosmanen and Kortetlainen, 2004; Navrud and Prucker, 1997).

In fact, many non-market valuation studies in the literature have suggested different methods for measuring WTP. For example, Sansa and Kasake (2004) identified two approaches for assessing demand or WTP. The first is the demand curve approach, which entails making observations on prices and quantities in a market. A demand curve is estimated, and WTP can be inferred. The second approach is the contingent valuation method (CVM) which is a survey-based technique that uses responses to some questions posted to the consumer on their preferences and WTP for a hypothetical product or service.

Khan (2007) has also discussed a number of methods to estimate demand or WTP for environmental services which includes indirect and direct methods. The direct method is a technique that relies on an individual's actual behavior in markets for goods with a relationship to the environmental service. The indirect method is a technique that mainly relies on an individual's hypothetical behavior with respect to markets set up for the environmental service.

In similar manner, Freeman (1993) divided valuation methods for non-marketed goods into direct and indirect methods. He stressed with indirect methods that include the travel cost method and hedonic pricing, the estimations are based on the observed behavior of individuals in the market of a good or service related to the interest. Direct methods, on the other hand, try to elicit information about the value of the non-market good or service directly from the individual. Among the methods in this category are valuation and choice modeling.

Furthermore, three methods for estimating WTP were recognized by Ranji and Elizabeth (2009). The first one that is based on observed various market prices for goods (i.e. water vending, buying from neighbours, paying local taxes). The second technique is based on observed individual expenditures of money, time, and labour to obtain goods or to avoid their loss. This method might involve an assessment of coping strategies and involve observations, focus group discussions and even household surveys. The third method is based on asking people directly what they are WTP for goods or services in the future. The first two approaches are based on observation of behavior and are called revealed preference techniques. The third technique is based upon a stated preference that includes the contingent valuation methodology.

Based on this fact, there are two methodological approaches broadly identified in the literature; revealed preference methodologies and stated preference methodologies. The revealed preference methods are derived from prices paid for goods or services (i.e. real monetary exchanges in a market place that reveal the preference of buyers); hence, they only measure use values (Boyle, 2003). It may sound paradoxical that non-market goods and services are sometimes valued based on revealed preferences, but this approach is used to bring out non-market components that are contained in market-priced goods or services.

On the other hand, stated preference methods reflect a WTP for a good or service presented to respondents in hypothetical scenarios (Brown, 2003). Using the case of fuel pellets, it is possible to value, for example, the benefits associated with an improved energy commodity compared to the traditional fuel wood used by households where availability, easy transportation, suitable storage and use in stoves are considered.

In order to address the effect of these market challenges, economists have developed a number of methods for environmental valuation. The principal among them is the contingent valuation technique, which elicit people's preference for environmental goods and their WTP for specified environmental improvements in terms of monetary values. This is done by using surveys where hypothetical markets are established among the people to indicate the amount that they will be WTP for a product or environmental improvements (Bateman and Kenneth, 2001; Mishra 2003).

As shown in the literature review, CV is a very useful technique by virtue of its universality (Cummings *et al*, 1986; Mitchell and Carson 1989; Hehneman 1994). It may be applied in most situations, and may, in fact, be the only practicable method of valuation of goods and services in certain situations (Al-Kandari, 1994).

A review of numerous literature on CV (Boyle and Bishop, 1988; Mitchell and Carson, 1989; Danaldson *et al*, 1999; Abdul Rahim 2008) shows that, in designing a CV questionnaire, it is important that respondents' familiarity with the good or service is taken into account, as well as a specific detail about the nature of the good and changes to be valued. The choice scenario must also provide an accurate and clear description of the change in environmental services associated with the event, program, investment or policy choice under consideration. There is also a need to determine the extent of the affected population or markets for the good or service in question, and ensure the survey sample is chosen based on the appropriate population.

In addition to the hypothetic question that asks for WTP, the survey must specify the mechanism by which the payment will be made, for example, water bill or through increased taxes. For validity, the respondents should be constantly reminded to consider budget constraints and the frequency of payments required, for example, monthly or annually, and whether or not the payments required over a long period of time in order to maintain the quantity or quality change. Last but not the least; the survey should also elicit socio-economic characteristics of the respondents who are usually regressed against WTP values as independent variables. In summary, according to Mitchell and Carson (1989) the survey consists of three parts.

- The first part gives a precise description of the good that has to be valued and of the hypothetical circumstances under which the public good is to be made an available substitute, and the method of payment.

- The second part consists of questions intended to elicit the respondents' (WTP) for the defined change of availability of the environmental good. It is often desirable to ask respondents to specify the reasons for their reported choices especially when respondents report they are not WTP anything. Adding a question for the reason of their zero answer can identify whether their true valuation is zero, or they protest against hypothetical market or method of payment.
- The third part of the survey asks for the characteristics of respondents. This information is used to explain the WTP of the respondents and to determine the validity and reliability of the CV method as a measuring instrument for environmental goods.

Although the CV method is simple and a flexible non-market method, it has been somehow controversial with a number of biases noted throughout the literature. The major according to Mitchell and Carson (1989) includes hypothetical bias, embedding effect, strategic bias, bid vehicle bias and starting point bias. Hypothetical bias arises because CV interviews create artificial markets, and respondents do not actually have to pay their stated amounts. Embedding effect occurs if respondents embed the good in question within a broader good when indicating their WTP for the good.

Economists have responded to the potential biases by continually making improvement to the CV methodology. One of the responses to these attacks is to argue that CV methods can be valid estimates of resources' values if studies are done carefully because improper administration and implementation of the CVM is one of the major sources of these biases. This is the position taken by many practitioners of the CV method (Randall *et al.*, 1983; Brookshire and Coursey, 1987). Also pretesting for the interview schedule and pilot studies should be made a precondition in any CV study. This will reduce certain biases in the preliminary stage of the survey itself.

In its purest form, CV methodology is a tool that stimulates a market for a non-market good and obtains a value for that good, contingent on the hypothetical market described during the survey. In conformity with CV guides, the study discussed in this thesis, involved carrying out a house-to-house survey, asking households a range of questions about their existing waste collection and disposal practice coupled with other socio-economic and demographic characteristics.

2.6.2 Empirical literature on valuation of goods or services.

There are several valuation studies conducted to justify the need for improved goods or services in different countries of the World. However, there is no economic study on pellet production in Nigeria. Most research done is based on improving waste collection and services, and not in the area of conversion into identified energy products. This study broadens the review on valuation, particularly the empirical studies in Nigeria.

Using the Tobit and Probit model, Amiga (2002) analysed perception and attitude of households towards solid Waste Management, their WTP for improved solid waste collection and the extent of cost recovery based on the amount household are WTP. Results from 430 randomly selected households surveyed in Addis Ababa using CVM show that, though 54.86 % of the respondents received waste collection services, 33.98 % practice illegal dumping and the vast majority of the households (91.02 %) are not satisfied with the city authority's Waste Management services but are willing to share the financial burden with the government. The mean monthly WTP was Birr 7.07 per household. Evidence from Tobit's analysis revealed income, time spent in the area, quantity of waste generated, responsibility of solid Waste Management, education, house ownership, number of children and age are significant variables in explaining maximum WTP. While in the Probit model result, income, age, number of children, time spent in the area, quantity of waste generated and education have significant effect on the WTP. From this result, the author expressed optimism that there was a good chance of success if solid waste collection charges were introduced, but the charges should take into cognizance both ability and WTP.

Alnaa *et al.* (2009) conducted a CV study with the objective of determining the amounts individual households are WTP for refuse management and factors that might influence people's demand for refuse management in Bogatanga Municipality, Ghana. The analysis of covariance conducted by the authors revealed the WTP was 16,750 currency?). The income variable had a significant effect on the WTP while occupation, level of education, interaction between sex and occupation, the interaction between sex and education as well as income, which s the covariate was all significant. From their findings, the authors concluded the responded are WTP but the levy should be below the mean WTP.

Mahanta and Das (2011) used both Cv method and logit models to analyse the problems of solid Waste Management and households' WTP for improvements in Waste Management (collection and disposal) in Guwahati, India. A two-stage sampling technique was applied to collect information from 360 randomly selected households. The findings revealed on average households within the city are willing to pay Rs. 60.22, though, a meager percentage of low-income groups showed a zero WTP. The authors believed zero WTP can be handled by other means like pursuing low-income earners to pay, introducing lower charges or making them t work instead of paying money. Based on the research findings, they suggested door to door waste collection service should be implemented as households have shown a WTP. They further added due to failure of local authorities to manage waste collection and disposal, the concept of public-private partnership should be introduced.

Energy commodity options of households is influenced by economic conditions, level of income, level of education, availability as well as other social characteristics (Naibbi and Richard, 2013, Momodu, 2013). The factors influencing household's choice for improved waste collection and disposal services are similar to that of choice in energy commodities therefore, the application of CVM to determine household's WTP will provide the basis for setting the price for cassia tora fuel pellets in Nigeria.

2.7 Energy sources and utilisation in Nigeria

Energy plays a significant role in the production of goods and service in every country's industry, transport, agriculture, health and education services. Nigeria is blessed with abundant sources of renewable and non-renewable energy with the share of various energy sources in the primary energy supply made up of oil 10.4 %, gas 6 %, hydro 0.6 % and renewable energy 83 %, with the renewable energy constituting waste and agricultural waste (UNDP 2002). Inefficiency in utilisation (Sambo, 2012) couple with weak government motivation, lack of economic incentives and corruption (Opara, 2013) have contributed to the energy poverty experienced by the country's economic sectors. Moreover, Nigeria has the lowest energy consumption rate in Africa (Mohammed and Petinrin, 2014). This has greatly affected the growth of the economy of the domestic sector, as energy use and economic growth are interrelated (Nwofe, 2013). Fuelwood remains the dominant source of energy for household activity's consuming about 80 % thus, resulting in increased deforestation, bio diversity loss, soil and environmental pollution (Momodu, 20013).

Oyedepo, (2014) in his research ''towards achieving energy for sustainable development in Nigeria'', examines the perspective of energy efficiency and renewable energy in the making of strategies for sustainable development in

Nigeria. The strategies according to him involve energy savings on the demand side, efficiency improvements in the energy production and replacement of fossil fuels by source of renewable energy.

Emodi and Vincent (2014) describe the energy situation (electricity) in Nigeria as epileptic with no sign of improvement and the situation has affected the manufacturing, services and residential sectors of the economy with reasons due to inefficient power plant, poor transmission and distribution facilities.

Oyedepo (2013), in his studies reviewed the energy pattern in Nigeria and concluded that sustainable energy systems are necessary to save the natural resources. Research by Audu (2013) on fuelwood consumption and desertification in Nigeria has identified fuelwood as the only means of domestic fuel in the Northern part of the country. He stressed the need to make available other means of domestic fuel and ensure continuous and constant supply. This will be a major contributing factor among measures of mitigating desertification. Ikurekong et al.,(2009) conducted research to investigate the use of fuelwood in rural and coastal fishing communities in Nigeria. They concluded that unavailability of other energy commodities. Major contributing factor of fuelwood exploitation. According to Mohammed *et al*. (2014), Nigeria has the bioenergy potential for power generation. Modern biomass technologies have yet to gain recognized attention in the country, and this has been the major setback in sustainable energy development facing the country. They suggested that government should create awareness and foster investment opportunities through media campaigns, research and development funding and effective bioenergy policy implementation.

Babanyara and Saleh (2010) are of the same opinion that fuelwood consumption has negative effects on the environment, especially in the area of desertification but observed the factors causing fuelwood demand to be due to rural-urban migration. Maconachie *et al.*, (2009) argued that rising prices of kerosene and other petroleum-based domestic fuels, coupled with economic knockoffs are responsible for the domestic fuelwood choice. Moreover, Sambo (2009) reported the availability of agricultural waste and sawdust at an annual estimation of 11.244 and 1.8 million tonnes, and if properly harnessed generate the energy equivalence of 147.7 X 10^3 MJ and 31.433 X 10^3 MJ respectively.

Mohammed *et al*. (2014) in their review of renewable-energy resources for power generation in Nigeria, reported an estimate of 697.15 TJ of energy equivalent availability in crop residues alone while 455.8 PJ is in animal waste. Although, Nigeria has an abundance of biomass energy resources, which are not properly harnessed, the region is affected severely in terms of energy poverty and environmental hazards (Naibbi and Richard, 2013) and this calls attention for research and development for improved energy fuels in the region.

From the review the major gaps in knowledge can therefore be sumarrised as thus;

- Wood materials from forest industries bi-products and agricultural wastes and residues have been the common materials for pellet making, and different methods are employed in pellet making (industrial and laboratory), most of the methods reported do not give much flexibility in terms of production process parameters with regards to laboratory scale production and no evidence is available with regards to making of cassia tora stems into pellets using any of these methods.
- The physical and chemical properties of biomass pellets have been studied with the aim of understanding their effect with regards to transportation, storage and application in biomass fuel combustion equipment.
- Production and continuous combustion of pellets for energy requires storage for variable periods of time. Though there is existing literature on biomass and biomass fuel storage, the effect of production conditions on the properties of stored pellets is limited, indicating that cassia tora stem pellets as a source of energy have not been investigated.
- The literature available on economics of pellet production were studied and there is no existing evidence of pellet production in Nigeria therefore, contingent valuation and willingness to pay analyses were also studied with the aim of understanding possible market value and acceptability of the fuel pellet.
- Willingness to pay for a new product and literature related to costing of environmental services (solid waste collection and disposal) was studied

with the aim of understanding and applying the methods in establishing the price of cassia tora pellets in Nigeria.

3. CASSIA TORA STEM PELLETS PRODUCTION AND CHARACTERIZATION

3.1 Introduction

Compacting biomass into a densified energy product with a uniform shape, such as a pellet, facilitates its handling, storage and transportation. It also brings about improvements in the properties of the solid material which helps in its usage as a feed stock in various energy conversion processes.

Pelletisation reduces transport costs, provides better handling and feeding of biomass fuel with less dust formation. The quality of biomass pellet, as mentioned earlier (Chapter 2), depends on its chemical, mechanical and physical properties in terms of thermal utilisation (Kaliyan and Morey, 2009; Obernberger and Thek, 2004). Some of these qualities or parameters are related to the type of raw material used (Arshadi *et al*., 2008; Rhen *et al*., 2005), while some are related to the quality management of the manufacturing process (Gilbert et al., 2009; Lehtikangas, 2001; Li and Liu, 2000).

Although the energy content is a very important quality of biomass fuel, emissions generated during combustion of the pellet and the suitability of the pellet for use in boilers and stoves is also an important concern of the end-users. Emissions from low quality biomass fuels can damage combustion equipment and undesired effects such as slagging, corrosion, and interference with process control (Lehtikangas, 2001). Low durability of biomass pellets results in a high content of dust or fine particles in the fuel, which can disturb the regulation of highly automated heating systems or interrupt fuel feeding (Li and Liu, 2000). Consequently, standard organisations (CEN/TC 335, ONORM, DIN and ASABE) for solid fuels have developed guidelines in the production and testing of biomass solid fuels to enhance its qualities for storage, transportation and combustion (Oberberger and Thek, 2004). The physical and chemical properties considered include; particle and bulk densities, moisture content, compressive strength, durability, particle size and pelle+t dimensions, proximate and ultimate analyses, and heating values.

The purpose of this chapter concerns the investigation and discussion of the production and characterisation of fuel pellets from cassia tora stems. Production involves the grinding of the stems, particle size distribution, binder and moisture addition, and manufacture of the pellet mould. The mould is based on a type adopted by Eggerstedt and Wang (2014) and Kaliyan and Morey, (2010) for flexibility in the manipulation of the production temperatures and pressures in the laboratory. Characterisation of the pellets included determination of calorific value, proximate and ultimate analyses, elemental analysis, bulk density, specific density, compressive strength, and durability. The physical and chemical properties of the produced pellets were tested according to the guidelines set by CEN/TC 335 and ASABE and the results were compared with the standards set by CEN/TC 335, ONORM, and DIN and the values obtained in related literature references.

3.2 Materials and methods

3.2.1 Cassia tora stem

Cassia tora plants were collected from the farmland area of the Kura local government area of Kano state (latitude; 11°30'N and longitude; 8°30'E) in October 2012. It was allowed to naturally dry in open atmospheric air and the leaves separated locally by means of hitting with sticks and winnowing in open air. The stem was crushed locally using a mortar and pestle Figure 3.2. The raw material was ground to smaller particle sizes using a hammer mill. The ground material was then collected and a sieving method, according to the standard CEN/TS 15149-2, was used to collect particle sizes of the milled cassia tora stems for the production of the fuel pellets (see Figures 3.1 , 3.2a-c). For the production of good quality pellets, a particle size range of 1 - 2.5 mm was used, as suggested by Kaliyan and Morey (2009; 2006) and Mani *et al*. (2004; 2002). The milled sample was weighed (100 g ± 2) and placed in sieves with different aperture sizes using Heico standard sieves (Hs 32.4) and a size range of 850 μm to 3.35 mm; the percentage of the fractions of each size was determined and are given in Table 3.1.

The dry raw material was weighed and 9 % by weight of a binder (solid gum Arabic) added. The binder addition was made to improve the quality of the pellets (Lehman *et al*., 2012). The content of carbon, hydrogen and nitrogen (C, H and N), and gross calorific value (GCV) of the gum arabic used were determined and the results are presented in Table 3.2.

Table 3.1: particle size distribution of cassia tora stems used for the production of cassia tora pellets

Aperture size	percentage of fraction
3.35 mm	0
2.8 mm	1.2
2.36 mm	2.3
2 mm	25.4
1.7 mm	17.6
1.4 mm	23.2
1.18 mm	14.3
1 mm	6.2
0.850 mm	9.4
Total	99.6

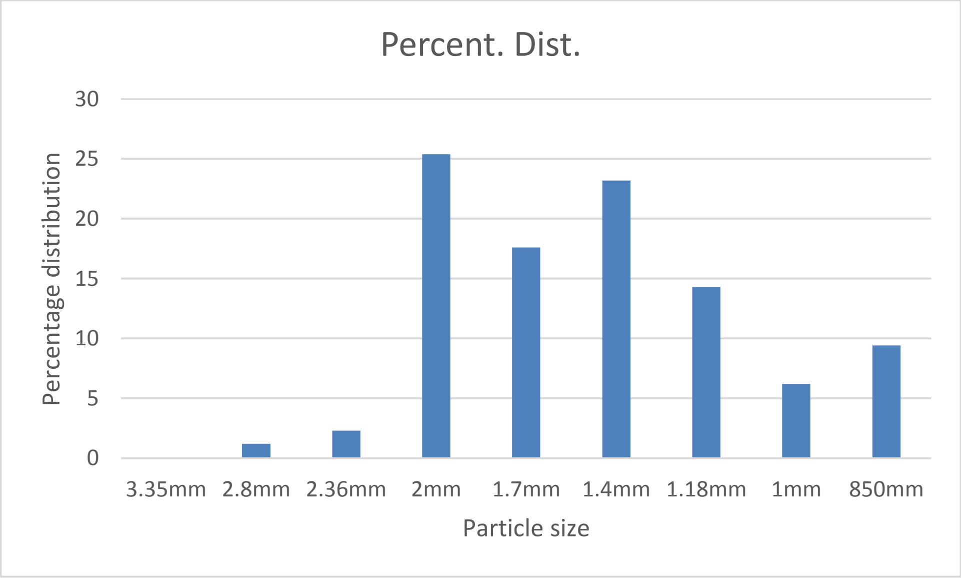

Figure 3.1: percentage distribution of particle size

The moisture content of the raw material was adjusted by mixing with water (10 % weight basis) to serve as a lubricant and also reduce the rigidity of the particles, the aim being a high density and quality biomass pellets (Shaw and Tabil, 2007; Kaliyan and Morey 2006; Mani *et al*., 2006; Obernberger and Thek, 2004; Li and Liu, 2000; Hill and Pulkiness, 1988).

3.2.2 Pellet production

The mould (Figures 3.3a and b)

A stainless steel mould was manufactured with six pellet chambers of diameter 12 and 14 mm for the experimental pellet production. The lower part of the mould containing the die has a heating band tighten up around it which is connected to a temperature control regulator with an automatic on and off switch control. A thermocouple was connected in circuit with the switch and electricity supply to the heater band. The other end of the thermocouple was fixed at the centre of the mould to sense the temperature rise within the body of the mould. This allows for the regulation of the temperature through a sensor located in the automatic control system by selecting the desired temperature needed for a specific condition of pellet production. The switch turns off with a small increase over the desired temperature set for production and turns on when the temperature goes lower than desired.

The upper part of the mould holds six sets of plungers aligned to the 12 and 14 mm diameter die chambers of the lower part. The 12 mm die holes and their corresponding plungers serve as guide for aligning the other 14 mm die holes and plungers when a pellet of 14 mm diameter is to be produced. A stopper is located at the bottom face of the lower mould to prevent the material from escaping during pelletisation.

Pelletising

The cassia tora ‘grind’ was added into the die holes of 14 mm diameter by means of a funnel. The stopper was aligned to the bottom of the lower part of the die and screwed with the support and blocking the holes from the bottom. The material was filled to the brim of the die and the mould was shaken to allow even settlement of the materials before compression. The top of the upper mould was aligned to the pressing head of the pneumatic press. The production temperature was set from the temperature regulator and the heating band allowed to heat the mould until an even distribution of heat was attained. The material was then introduced into the mould, the plungers set to the dies and load applied from the press (a Cussons p5030) at 25 mm/min until the desired compression force was achieved. The pressure was maintained for 2 min (hold time) to allow for even distribution of the force and also to prevent the material from sudden relaxation on immediate release of compression (Adapa *et al*., 2006; Mani *et al*., 2006). When the pressure was released, the stopper was removed from the bottom of the mould and the pellets pressed out. The pellets were allowed to dry and cool before storing.

The pellets were produced at 50, 70, 90, 120 and 140 MPa and pressing temperatures of 30. 60, 75, 90, 105 and 120^{o}C.

The pellets were then stored in sealed plastic bags before further analysis was carried out. For each experimental condition (at each production temperature and pressure) 10 sets of pellets were repeatedly made, to allow for steady and increased accuracy of production.

Figure 3.2 a: crushing cassia tora stems in a mill

Figure 3.2 b: cassia tora grind before sieving

Figure 3.2 c: cassia tora stem grinds after sieving

Figure 3.3 a: lower part of the mould connected to temperature control.

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Figure 3.3 b: upper part of the mould

Figure 3.4(a) : cassia tora pellets produced at 50 MPa/30^{o}C.

Figure 3.4 (b) : cassia tora pellets produced at 140 MPa/120ºC.

Table 3.2: Elemental analysis and gross calorific value of the binder (gum Arabic) used in the pellet production

Element	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	V
	%	%	%	%	%	%	%	%	%	%	%
	< 0.51	0.589	0.498	1.427	0.0317	0.1221	0.1346	0.802	1.119	< 0.00071	< 0.0013
Element	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Rb
	%	%	%	%	%	%	%	%	%	%	%
	0.0426	< 0.00065	0.01413	< 0.00066	0.00127	0.00036	< 0.00021	< 0.00017	< 0.00012	< 0.00011	0.00316
Element	Zr	Nb	Mo	Ag	Cd	In	Sn	Sb	Te	I	Cs
	%	%	%	%	%	%	%	%	%	%	%
	< 0.050	< 0.0013	< 0.0028	0.00135	< 0.0023	< 0.0013	< 0.0027	< 0.0023	< 0.0033	< 0.0060	< 0.0083
Element	Ce	Hf	Ta	W	Hg	Tl	Cr	Mn	Sr	Y	Ba
	%	%	%	%	%	%	%	%	%	%	%
	< 0.020	< 0.00072	0.00691	< 0.0012	0.00021	< 0.00029	0.0088	0.0609	0.00207	0.00087	< 0.012
Element	La	C	H	N	O						
	%	%	%	%	%						
	< 0.016	39.25	5.81	0.27	54.54	GCV kJ/kg	15810				

3.2.3 Determination of the physical characteristics of the pellets.

a) Dimensions

The mean dimensions of the pellets were determined by measuring the length (L) and diameter (D) of 20 randomly selected pellets. This is in line with CEN/TS 14588:2005 standards of measuring the dimensions of fuel pellets. The mean values and standard deviation are given in Tables 3.3 a-e.

b) Bulk density, B

CEN/TS 15103:2009 standard test for bulk density was employed, where a graduated cylindrical container of 0.5 l was used to determine the volume of a sample. The cylinder was gradually filled with the pellets. Firstly, the cylinder was filled to one-third and it was tapped on a table to allow the pellets to settle down, then it was repeated for the second and the third filling. The bulk density was calculated by dividing the mass of the weighed sample by the volume in kg/m^3. The mean values and standard deviations are given in Tables 3.3 a-e.

c) Particle density, P

The particle density of the pellets were determined (as in CEN/TS 15150:2006) by measuring the dimensions and weight of randomly selected pellets and the average values of the measurement were used in the calculation of the particle density. The mass of the pellets was divided by the measured volume in kg/m^3. The mean values and standard deviations are presented in Tables 3.3 a-e.

d) Durability, D

The specification CEN/TS 15210-1-2006 was used where 500g of the pellets were put into a rotating drum and made to rotate at a fixed speed (50 rpm for 10 min). The sample was weighed before and after the test. The difference in mass was calculated as the percentage durability of the pellets. The lower the difference the higher the durability. The percentage of the remaining pellets were recorded and presented in Tables 3.3 a-e.

e) Compressive force

A Cussons P5030 material testing machine was used to test the compression strength of the pellets. The pellets were placed between two flat, parallel platens which have a facial area greater than the projected area of the pellets. An increase in load was applied at constant rate, until it failed by cracking. The load at which the cracking occurs was then recorded. According to ASABE (2008), all the pellets' samples subjected to this test have to be adjusted to have the same length. To take care of this and to avoid uneven pellet length in the event of the test, the test conducted was measured per length of each sample. The results are given in Tables 3.3 a-e.

3.2.4 Determination of chemical properties

Calorific values, proximate and ultimate analyses were tested for pellets produced at 50, 90, 140 MPa and 30, 60, 90 and 120^{o}C only, and the result is presented in table 3.4.

a) Gross calorific values

This was carried out according to the CEN/TS 14918:2005 standard, where a bomb calorimeter was used in the determination of the calorific value of the pellets. In the bomb calorimeter, combustion occurs at constant volume and is a non-flow process. The pellet was ignited by fusing a piece of platinum wire which was in contact with it. The wire forms part of an electric circuit which was completed by a firing button situated in a position remote from the bomb. The crucible carrying the pellet was located in the bomb and a small quantity of distilled water was put into the bomb to absorb the vapours formed by combustion and ensure that the water vapour produced is condensed. The top of the bomb was screwed down. Oxygen was admitted slowly until the pressure was above 23 atmospheres. The bomb was located in the calorimeter and 2.1 l of water was poured into the calorimeter. The calorimeter was then closed and the external connections to the circuit made, and a Beckman thermometer was immersed to the proper depth in the water. The water was stirred in a regular manner by a motor driven stirrer and temperature observations were taken every minute. At the end of the fifth minute the charge was fired and the temperature readings were taken every minute during this period. The time and temperature changes for pre-firing, heating and cooling were recorded. The measured temperature was corrected for various losses. The water equivalent of the calorimeter was determined by burning benzoic acid. The calorific values for pellets under investigation were then calculated using the equation below:

$$M_f * Cal = (M_w + W_{eq})(C_{temp} * Cp_w) \quad 3.1$$

Where, M_f is the mass of fuel, M_w is the mass of water and Cp_w is specific heat capacity of water, *Cal* is the calorific value, W_{eq} is the water equivalent of bomb and C_{temp} is the corrected temperature Rise..

b) Proximate analysis

Proximate analysis was done in order to determine the moisture, volatile matter, fixed carbon and ash content of the pellets according to the following standards;

i. CEN/TS 14774-1:2009

The water content (moisture) was determined by weighing a pellet sample (about 100 g (w.b.)) before and after drying at 105^{o}C for 60 mins. An empty metal tray was weighed to the nearest 0.1 g using a weighing balance. The pellet sample was then transferred into the tray and weighed before placing in an oven. The oven was set at 105^{o}C and the plate placed in the oven for 60 min. The plate was removed and immediately weighed to avoid moisture absorption by the sample before weighing. The moisture was calculated using the following expression:

$$Mar = \frac{(m2 - m1) + m4}{(m2 - m1)} \; x \; 100 \quad 3.2$$

Where, *m1* is the mass of the empty metal container, *M2* is the mass of the container and sample before drying, *M3* is the mass of the container and sample after drying and *m4* mass of the moisture associated with the packing.

ii. Volatile matter according to CEN/TS 15148:2005;

The volatile matter content was determined by driving off the hydrocarbons and the moisture by burning the pellet in a covered crucible, in a muffle furnace at 900ºC±10ºC for 7 min. The crucible was weighed before and after the sample was placed, and after burning in the oven. The difference between the initial weight of the pellet before burning and the weight of the ash was calculated as volatile matter contained. This was calculated according to the equation;

$$Vd = \left[\frac{100\,(m2-m3)}{M2-M1} - Mad\right] \text{x} \left(\frac{100}{100-Mad}\right) \qquad 3.3$$

Where, *m1* is the mass of the empty crucible, *m2* mass of the crucible and sample, *m3* mass of crucible and sample after heating and *Mad* moisture percentage by mass of the sample.

iii. Ash content

The amount of ash remaining after the combustion was measured according to CEN/TS 14775:2004. A 1 g milled pellet was placed at the bottom of a porcelain dish and spread in an even layer over the bottom surface. The sample and the dish were weighed to the nearest 0.1 mg and heated in a two-step manner. At first the temperature was raised to 250^{o}C±10^{o}C for 60 min and then the temperature was raised to 550^{o}C and maintained for 120 min. The dish was removed and allowed to cool before weighed to the nearest 0.1 mg. The ash content was then calculated using the following equation;

$$Ash = \frac{(m2-m3)}{(m2-m1)}\ x\ 100\ x\ \frac{100}{100-Ms} \qquad 3.4$$

Where, *m1* is the mass of empty dish, *m2* is the mass of dish and sample, *m3* mass of dish and ash, and *Ms* percentage moisture of the sample.

iv. The fixed carbon was calculated by difference using equation:

$$C = 100 - (M+V+A) \qquad 3.5$$

Where, *M* is the moisture content, *A* is the ash residue and *V* the volatile matter all expressed as percentages.

c) Ultimate analysis

The main chemical elements in carbonaceous solid materials (apart from associated mineral matter) are carbon (C), oxygen (O), hydrogen (H), nitrogen (N) and sulphur (S). The C, H, N, and O values were determined for pellets produced at 50 MPa/30^{o}C and 140 MPa/120^{o}C before and after a storage period of six months. The results are presented and discussed in Chapter 5.

3.3 Results and discussion

Table 3.3a: Physical properties of cassia tora stem pellets at 50 MPa pressure and different temperatures of production condition.

temperature	L(mm)	S.D	D (mm)	S.D	P (g/mm^3)	B (kg/m^3)	S.D	Du (%)	CS (Nmm^{-2}) x mm	S.D
30^{o}C	47.35	±2.24	14.45	±0.87	0.001517	617.34	±22.1	60	27.5	±0.23
45^{o}C	47.35	±2.32	14.45	±0.65	0.001517	617.34	±22.42	60	27.5	±0.28
60^{o}C	47.24	±2.43	14.3	±0.54	0.001553	617.37	±20.6	62	30.4	±0.22
75^{o}C	46.72	±3.21	14.3	±0.67	0.001570	617.37	±21.14	75	37.5	±0.34
90^{o}C	46.38	±3.23	14.15	±1.32	0.001616	617.42	±18.65	87	37.5	±0.45
105^{o}C	46.38	±2.46	14.15	±0.97	0.001616	617.42	±20.45	87	37.5	±0.35
120^{o}C	36.38	±2.54	14.15	±0.84	0.001616	617.42	±21.34	87	37.5	±0.43

Table 3.3b: Physical properties of cassia tora stem pellets at 70 MPa pressure and different temperatures of production condition.

temperature	L(mm)	S.D	D (mm)	S.D	P (g/mm^3)	B (kg/m^3)	S.D	Du (%)	CS (Nmm^{-2}) x mm	S.D
30^{o}C	46.1	±2.23	14.5	±1.17	0.001569	617.40	±20.67	60	37.80	±0.45
45^{o}C	46.1	±2.44	14.4	±1.43	0.001569	617.40	±20.39	60	37.80	±0.37
60^{o}C	46	±2.65	14.3	±1.32	0.001595	617.40	±21.43	75	37.80	±0.54
75^{o}C	45.8	±3.23	14.3	±0.98	0.001640	617.40	±23.18	87	37.80	±0.78
90^{o}C	45.8	±2.65	14.1	±0.78	0.001648	617.48	±22.45	92	37.80	±0.58
105^{o}C	45.8	±2.12	14.1	±1.21	0.001648	617.48	±21.34	92	37.78	±0.76
120^{o}C	45.8	±2.14	14.1	±0.92	0.001648	617.48	±21.43	92	37.82	±0.68

Table 3.3c: Physical properties of cassia tora stem pellets at 90 MPa pressure and different temperature of production condition

Temperature	L(mm)	S.D	D (mm)	S.D	P (g/mm^3)	B (kg/m^3)	S.D	Du (%)	CS (Nmm^{-2}) x mm	S.D
30^{o}C	45.23	±3.14	14.32	±0.87	0.001617	617.68	±21.37	64	39.85	±0.86
45^{o}C	45.23	±3.23	14.32	±0.74	0.001617	617.68	±21.34	64	39.85	±0.93
60^{o}C	45.21	±2.4	14.20	±0.68	0.001645	617.72	±21.45	80	57.40	±1.21
75^{o}C	45.21	±2.1	14.20	±0.54	0.001646	617.78	±21.38	88	58.32	±1.07
90^{o}C	45.10	±2.17	14.20	±0.53	0.001669	617.84	±20.43	93	58.7	±0.97
105^{o}C	45.10	±2.33	14.10	±0.65	0.00173	617.84	±22.31	93	61.2	±0.84
120^{o}C	45.10	±2.47	14.10	±0.67	0.00173	617.84	±21.34	93	61.2	±0.77

Table 3.3d: Physical properties of cassia tora stem pellets at 120 MPa pressure and different temperature of production condition

Temperature	L(mm)	S.D	D (mm)	S.D	P (g/mm^3)	B (kg/m^3)	S.D	Du (%)	CS (Nmm^{-2}) x mm	S.D
30^{o}C	45.10	±2.83	14.30	±0.79	0.001627	617.60	±22.17	67	40.50	±0.43
45^{o}C	45.10	±2.34	14.30	±1.32	0.001627	617.67	±20.76	67	45.85	±0.51
60^{o}C	45.10	±2.17	14.20	±0.97	0.001650	618.20	±20.39	86	51.60	±0.62
75^{o}C	45.05	±2.22	14.08	±0.93	0.001652	618.20	±22.37	91	61.40	±0.57
90^{o}C	45.05	±2.13	14.08	±0.67	0.001680	618.40	±22.43	93	63.2	±0.73
105^{o}C	45.05	±2.27	14.08	±0.97	0.001680	618.40	±22.14	93	63.2	±0.34
120^{o}C	45.05	±2.33	14.08	±0.89	0.001680	618.40	±22.32	93	63.2	±0.47

Table 3.3e: Physical properties of cassia tora stem pellets at 140 MPa pressure and different temperature of production condition

temperature	L(mm)	S.D	D (mm)	S.D	P (g/mm^3)	B (kg/m^3)	S.D	Du (%)	CS (Nmm^{-2}) x mm	S.D
30°C	44.2	±2.21	14.30	±0.63	0.001660	617.80	±21.47	68	43.00	±0.37
45°C	44.2	±2.1	14.30	±0.68	0.001660	617.80	±21.38	68	51.31	±0.43
60°C	44.18	±1.97	14.24	±0.75	0.001675	618.40	±21.34	88	51.85	±0.47
75°C	44.18	±1.84	14.24	±0.59	0.001675	618.40	±20.98	93	61.40	±0.40
90°C	44.00	±1.63	14.04	±0.78	0.001732	619.2	±22.23	95	63.2	±0.39
105°C	43.70	±2.13	14.04	±0.81	0.001742	619.20	±20.84	95	63.4	±0.42
120°C	43.70	±1.42	14.00	±0.94	0.001752	619.20	±20.76	95	63.4	±0.43

Table 3.4: proximate analysis and gross calorific values (GCV) of cassia tora pellets produced at 50, 90 and 140 MPa with variation in production temperatures

pellet sample	moisture (% wb)	ash (% db)	volatile (% db)	fixed carbon (%)	GCV (MJ/kg)
$P_{50,30*}$	9.60	4.3	68.42	16.19	17.89
$P_{50,60}$	9.25	4.3	68.47	16.98	17.89
$P_{50,90}$	8.83	4.2	68.37	18.6	17.95
$P_{50,120}$	8.17	4.2	68.48	19.15	18.09
$P_{90,30}$	9.22	4.3	68.39	17.09	17.89
$P_{90,60}$	8.63	4.2	68.43	17.74	18.08
$P_{90,90}$	8.02	4.2	68.49	19.29	18.09
$P_{90,120}$	7.18	4.2	68.49	20.13	18.09
$P_{140,30}$	9.06	4.2	68.49	17.25	17.89
$P_{140,60}$	8.6	4.3	68.48	18.62	18.09
$P_{140,90}$	7.23	4.3	68.36	20.11	18.09
$P_{140,120}$	7.18	4.3	68.47	20.05	18.1

*****$P_{x,y}$ indicates pellets produced at *x* pressure and *y* temperature conditions

3.3.1 Dimensions of the pellets

The pellet diameters for all the production conditions of pressure and temperature ranges between 14 and 14.5 mm (Tables 3.3a-e). According to the Austrian Pellets Association (Table 3.6*)* the ratio length/diameter should be less than 5. From tables 3.3a-e the values of the ratio length/diameter of the cassia tora stem pellets ranges between 3.09 and 3.19 which falls within the provision of the standard. The results also indicate a relative decrease in the dimensions with increase in temperature and pressure.

3.3.2 Bulk density

The bulk density of the cassia tora stem pellets from Tables 3.3a-e varies between 619.2 and 617.09 kg/m^3. This falls within the standard provision of standards in Sweden, Italy and Spain (Table 3.6).

3.3.3 Particle density

From Tables 3.3a-e the particle densities of the produced cassia tora pellets range between 48 x 10^{-3} g/mm^3 and 52 x 10^{-3} g/mm^3 which is also in line with the Australian standards of commercial fuel pellets with the value of particle density to be greater than 1.12 x10^{-3} g/mm^3 (Table 3.6). Particle density influences the bulk density and also combustion behaviour of fuel pellets, the denser the particles the longer the time they will take to burn out.

3.3.3 Durability

According to ONORM M 7135 the durability of fuel pellets should not be less than 98.7%. The data in Tables 3.3 a-e shows a range of values between 60 -95 % for 50 MPa/30^{o}C-140 MPa/120^{o}C.The difference is seen to be due to the variation in the production condition of the pellets where the higher the production temperature and pressure the higher the durability and vice-versa. The pellets produced at 50 MPa/30^{o}C (Table 3.3 a) all have durability less than 90 %. While pellets produced at 70-140 MPa at temperatures between 90-120^{o}C have durability of ≤90 %. This has shown that higher durability pellets are produced at 90-120^{o}C when the pressure is ≤70 MPa.

The CEN/TC 335 standard specification (Table 3.6) for durable quality pellets is ≤90 % and this is achieved with the cassia tora pellets. Similar results were obtained for chestnut sawdust and pine sawdust pellets by Gil *et al*. (2010), while they observed a lower durability with coffee husks and grape waste pellets. Figure 3.6 shows the durability index at different production temperatures and pressures. Higher production temperatures are associated with higher durability. Although increase in production pressure have effect on durability, temperature is seen to have more influence on the durability of the produced pellets. According to Gil et al. (2010) a durability of 85 % is the minimum for a quality fuel pellet.

Durability has a significant effect on combustion systems where an increase in the amount of fines can cause failure in the feeding systems and also can have an effect on transportation and storage.

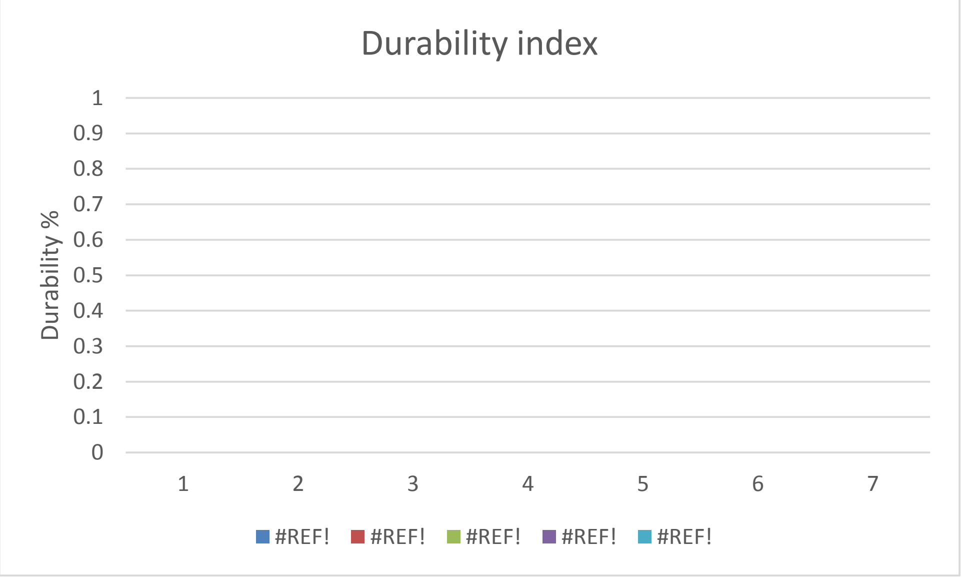


Figure 3.5: Durability index for pellets at different compression pressure where numbers 1-7 refers to temperature 30-120^{o}C.

3.3.4 Moisture

The moisture content of the cassia tora stem pellets is presented in Table 3.4. The pellets produced at high temperature and high pressure conditions have a lower moisture content with the least of moisture obtained at 140 MPa and 120^{o}C. The moisture content ranges between 7.18 and 9.6 % for highest pressure/temperature and lowest pressure/temperature, respectively. The moisture content has an influence on the gross calorific value, combustion efficiency and temperature of combustion. The higher the moisture content the lower the calorific value as noticed in Table 3.4.

3.3.5 Ash content

From Table 3.4 ash content varied slightly with production conditions of the fuel pellets, with the pellets produced at higher temperatures having a slightly lower ash content. Although the same materials were used in making the pellets, variation in production temperature and pressure could be responsible for the slight difference in the ash content. The amount of the ash content has also exceeded the standard ONORM 7135 specifications for commercial fuel pellets.

Table 3.5: Elemental analysis of ash content of cassia tora stem pellets

Element	Na%	Mg %	Al %	Si %	P %	S %	Cl %	K %	Ca %
	7.27	6.8	1.858	10.94	2.472	1.813	2.485	13.62	16.54
Element	Ti %	V %	Cr %	Mn %	Fe %	Co %	Ni %	Cu %	Zn %
	0.0709	< 0.0039	0.0081	0.114	2.072	< 0.0042	0.00824	0.01693	0.0416
Element	Ga %	Ge %	As %	Se %	Br %	Rb %	Sr %	Y %	Zr %
	0.00074	< 0.00026	0.00065	0.00018	0.00438	0.02586	0.1371	0.00104	< 0.050
Element	Nb %	Mo %	Ag %	Cd %	In %	Sn %	Sb %	Te %	I %
	< 0.0015	< 0.0063	0.00181	< 0.0015	< 0.0015	< 0.0038	< 0.0026	< 0.0036	< 0.0065
Element	Cs %	Ba %	La %	Ce %	Hf %	Ta %	W %	Hg %	Tl %
	< 0.011	0.2075	< 0.020	< 0.026	< 0.0018	0.0072	< 0.0015	< 0.00036	< 0.00036

The elemental analysis of the ash from Table 3.5 indicates the presence of a significant content of silicon, potassium, calcium and sodium (certainly for the silicon and possibly the other elements this maybe from the inevitable adhesion of a very small amount of soil to the cassia tora stems in collection). A high presence of silicon is possibly due to the presence of sand that got mixed up with the material during drying, grinding and other possible processes of the production.

3.3.6 Gross calorific value (GCV)

The gross calorific values from Table 3.4 are shown to be influenced by the presence of moisture, the higher the moisture content the lower the GCV. The variation in the production conditions have influenced the presence of moisture, especially the increase in the temperature of production, which relatively reduces the amount of moisture, which in turn increases the GCV. The results obtained for GCV ranges between 17.89 and 18.1 MJ/kg from the lowest to highest temperature/pressure conditions of production respectively. These values also fall within the standards of commercial fuel pellets by all the standard organisation (Table 3.6)

Table 3.6: Biomass pellets guiding standards for Austria, Germany and European standard committee.

pellet parameter	Austrian (ONORM)[1]	German (DIN)[1]	European S.C.(CEN/TS)[2]
Diameter (mm)	btw 4 to 10	btw 4-10	btw 6 to 25
Length (mm)	L < 5D	<5D	L ≤5D, for D=6 mm and L ≤4D for D= 8 to 25 mm
Part. Den.(g/mm3)	Part den > 1.12 x 10^{-3}	>1.2 x 10^{-3}	Not provided
Durability (%wt)	Du ≥97.7	Du ≥97.7	Du ≤ 97.5 to ≤90
Moisture (%w.b)	M_S <10	M_S <12	M_S ≤10 to ≤20
Ash content (%wt)	Ash <.5	Ash <1.5	Ash ≤ 0.7 to ≤6
GCV (MJ/kg)	18.0	15.50 to 19.50	Not provided
N (% wt)	<.3	<.3	≤ 0.3 to ≤ 3
S (% wt)	<.04	<.08	≤ 0.05 to ≤ 0.2
Cl (% wt)	<.02	<.03	≤ 0.03 to ≤ 0.01
As (mg/kg)	-	<.8	-
Cd (mg/Kg)	-	<.05	-
Cr (mg/Kg)	-	<8	-
Hg (mg/kg)	-	<5	-
Pb (mg/Kg)	-	<10	-
Zn (mg/Kg)	-	<100	-

3. Garcia et *al*., (2011)
4. CEN/TS 14961:E, (2005)

3.4 Conclusions

- The advantage of laboratory-scale production of biomass pellets is the room available for manipulations or adjustment of the production conditions. A mould was successfully adopted and used in the production of cassia tora pellets where the production temperature and pressure were varied to suit the investigations intended.
- With a GCV range of 17.89 to 18.1 MJ/kg, moisture content of 7.18 to 9.6 %, durability of greater than or equal to 90% for pellets produced at 90 to 120^{o}C with densification pressure greater than or equal to 70 MPa, cassia tora pellets product that is comparable to other biomass pellets has been achieved.
- The variation in production conditions (temperature and pressure) have influence on the quality of pellet as seen with the properties of the pellet
- The standard diameter of commercial pellets according to ONORM and DIN specifications is between 4 to 10mm with length of less than five times the diameter. If 10mm diameter is considered, then the length will have to be less than 50mm and according to these standards the ratio of length to diameter (L/D) will then be less than 5mm for 10mm diameter. But according to CEN/TS standard specification the length should be equal to or less than four times the diameter for pellets produced with diameter between 8 and 25mm. The pellets produced within the laboratory frame work of this research at 90Mpa and 120MPa have an average diameters 14.21 and

14.16mm with corresponding lengths of 45.17 and 47.07mm respectively. The ratios L/D is therefore 3.18 and 3.32. Although the diameter is larger than the specification of ONORM and DIN and of course lower L/D ratio, it has been in conformity with CEN/TS specifications since the length is less than four times the diameter and the produced cassia tora pellets' diameter falls within the range of 8 to 25mm. Furthermore, the parametric studies confirms that pellets can be could be made to every standard sizes if cassia tora were to become a traded fuel.

- Nitrogen (N); the specification for the amount of nitrogen content for ONORM and DIN is less than or equal to 0.3% and for CEN/TS is between less than equal to 0.5 and 3% and normative only for chemically treated biomass. The content of nitrogen as presented in Chapter5 is 1.48% which is expected of straws and grass pellets as with case of cassia tora pellets. Higher concentrations of nitrogen are normally found in straws and grasses. Nitrogen is almost entirely converted to gaseous N_2 and nitric acid during combustion, and emission of nitric acid is one of the environmental impacts of solid biofuel combustion. Thus means of reducing this emission need be addressed in combustion systems
- Sulphur; the specification for sulphur by ONORM is less than 0.04% and DIN is less than .08%, where as that of CEN/TS varies between less than 0.05 and 0.2 normative to chemically treated biomass and if sulphur containing additive is used as a binder. The content of sulphur as presented in Chapter 5 is 0.21%. This has been in

conformity with the highest level of sulphur expected from CEN/TS specification. The content of the 0.122% which is low and cannot be ascertain to have incremental effect on the sulphur content of the cassia tora pellets. Sulphur contained in solid biofuels forms mainly gaseous SO_2 and alkali as well as alkali earth sulphates. Combustion plants need be equipped with baghouse filters in order to integrate high percent of sulphur in the ash. Another problem that could be encountered is the formation of aerosol due to SO_2 gaseous emission during combustion. Provision of gas filters will highly reduce this emission related problem.

- The summary of parameters of the cassia tora determined and classified based on the standard specifications of ONORM, DIN and CEN/TS are presented in table 3.7. Cassia tora pellets produced at 90^{o}C and compression pressures of 90, 120 and 140MPa are presented and values of N, S and Cl are assumed uniformity within the production conditions of the pellet. Amongst the three conditions in consideration the best quality cassia tora pellets are produced at 90^{o}C and 140MPa.

Table 3.7: Cassia tora pellet classification base on the ONORM, DIN and CEN/TS specifications.

pellet parameter	90MPa at 90^{o}C	120MPa at 90^{o}C	140MPa at 90^{o}C	Remarks
Diameter (mm)	14.2	14.2	14.04	Higher than ONORM and DIN specification in all cases but fall within CEN/TS specifications
Length (mm)	45.1	45.1	44	Same as with diameter
Part. Den.(g/mm3)	1.7 x10^{-3}	1.7 x 10^{-3}	1.7 x10^{-3}	Conforms with the range of specification of ONORM and DIN
Durability (%wt)	93	-	95	Durability is below the standard of ONORM and DIN but falls within the specification of CEN/TS
Moisture (%w.b)	8.02	-	7.23	Moisture is in conformity with all standards
Ash content (%wt)	4.2	-	4.3	Ash content conforms only within the specification of CEN/TS
GCV (MJ/kg)	18.09	-	18.09	Pellets gross calorific value conforms with all the standards
N (% wt)	1.48	1.48	1.48	Nitrogen content is high as compared to ONORM and DIN but is within the range of CEN/TS specifications
S (% wt)	0.21	0.21	0.21	Sulphur content is only within the specification of CEN/TS
Cl (% wt)	0.32	0.32	0.32	Chlorine is high as compared with all standards

4. THERMOGRAVIMETIC ANALYSIS (TGA) AND DETERMINATION OF KINETIC PARAMETERS OF THE PRODUCED PELLETS

4.1 Introduction

Biomass is an important source of energy and largely responsible for the increase in renewable based energy production in the world. The burning of biomass releases CO_2 but then this is recaptured through photosynthesis (De Jong, 2003). The use of biomass for energy production in place of fossil fuels would reduce the amount of CO_2 emission to the atmosphere by more than 90% (De Jong, 2003; Hagedorn *et al*. 2003). The composition of biomass types comprises a number of constituents with complex structures that vary in physical and chemical properties. Different ratios and structures of hemi-cellulose, cellulose, lignin and extractive matter are present in biomass species. The knowledge of these properties helps in understanding the functional ability of biomass fuel in energy conversion equipment.

Kinetic information is very important in the design, development and modelling of technologies based on the pyrolysis and combustion of lignocellulose materials (Ella *et al*., 2005). The kinetic parameters determined in the pyrolytic characterisation of biomass are the activation energy (*Ea*), the pre-exponential factor (*A*) and the order of the reaction (Schniewind, 1989). Activation energy is the dominating factor in the reactivity equation when thermal analysis results are concerned (Ella *et al*., 2004). Activation energy is a term introduced in 1889 by a Swedish scientist called Svante Arrhenius. It is defined as the energy that must be overcome in order for a chemical reaction to occur. It may also be defined as the minimum energy required to start a chemical reaction. The activation energy of a reaction is usually denoted by *Ea* and given in units of kilojoules/mole. The activation energy typically affects the temperature sensitivity of the reaction rate while the pre-exponential factor is related more with material structure. Thus the reactivity of biomass material is characterised by its activation energy. Generally, determination of these kinetic parameters depends on experimental conditions such as heating rate, sample size, moisture content of the sample and the heating medium (Nugroho *et al.*, 1998).

Thermogravimetic (TGA) data is used in the determination of biomass kinetic parameters (Celyn and Topcu, 2014; Ibrahim *et al*., 2013; Pathasarathy *et al*., 2013; Polat *et al*., 2013; Yorulmaz and Atimtay, 2009; Mansaray and Ghaly, 1999). Quantitative methods are applied to TGA curves to obtain the kinetic parameters (Pathasarathy *et al.*, 2013).

The aim in this Chapter is to discuss the investigation into the combustion kinetics of pellets made from cassia tora stem which include; percentage by weight of cellulose and lignin content, moisture, and the determination of activation energy, pre-exponential factor and order of reaction.

4.2 Materials and methods

Pellet produced at 120 MPa and 100^{o}C was used for the TGA. The analysis was carried out using a PerkinElmer Pyris 1 TGA, controlled using

PerkinElmer Pyris thermal analysis software version 9.0. PerkinElmer standard pans were used and each pan was cleaned after each test before the next sample was introduced. TGA is achieved by heating the sample and volatile materials are released. The TGA gases were from oil-fired compressed air source with a flow of air at about 40 ml/min through the TGA balance purge inlet, and an additional purge of 40 ml/min through the sample purge inlet. This resulted in a total air flow of about 80 ml/min over the sample, as the two flows combined over the sample.

Calibration was done in order to provide an indication showing the correct temperature at the sample and also to provide an accurate measurement of the mass of the sample remaining during the measurement. Temperature was calibrated using certified Curie point calibration reference material supplied by the equipment manufacturer. The principle uses the temperature at which the material loses its magnetic properties when measured in magnetic field. In this case the reference materials were alumel, nickel and Perk alloy. The weight calibration uses a class 1.1 100 mg calibration weight supplied with analyzer by the manufacturer. The mass of the sample used in the analysis is 6.438mg and the analysis is done twice and average value is reported.

All calibration checks met the requirement to be within $\pm 5^oC$ of expected transition temperatures for the three temperature materials. (See appendices 1 and 2)

4.2.1 Calculation of kinetic parameters

In the determination of the kinetic parameters using TGA data a modified form of the Arrhenius equation by Pathasarathy *et al.* (2013) and Mansaray and Ghaly (1999) was used. The equation for the kinetics of the de-volatilisation reaction is written as;

$$-\frac{d\alpha}{\mathrm{dt}} = \mathrm{K}X^n \qquad 4.1$$

Applying the Arrhenius equation we have

$$K = Ae^{-E/RT} \qquad 4.2$$

Substituting for K in equation 4.1 will give

$$-\frac{d\alpha}{\mathrm{dt}} = Ae^{-E/RT}\alpha^n \qquad 4.3$$

Taking the natural log of both sides of equation 4.3 will give,

$$ln - \frac{d\alpha}{\mathrm{dt}} = ln\ A - \frac{E}{RT} + nln\alpha \qquad 4.4$$

But *α* is the change in weight of the sample at the stage of pyrolysis and can be written as

$$\alpha = \frac{w-wf}{wo-wf} \qquad 4.5$$

Where, *w, wo and wf* are weight of the sample at time *t*, initial weight and final weight respectively.

Putting the value of α into equation 4.5, we have a linear form of the equation below;

$$-ln[\frac{1}{wo-wf} \cdot \frac{dw}{dt}] = ln\ A - \frac{E}{RT} + nln[\frac{w-wf}{wo-wf}] \qquad 4.6$$

Taking the value of *n* to be unity in accordance with Serageldin and Pan (1983), the graph of $-ln[\frac{1}{wo-wf} \cdot \frac{dw}{dt}]$ was plotted against $\frac{1}{T}$ resulting in straight lines corresponding to the different temperature regions of the TG/DTG curve. The activation energy is then obtained from the slope of the graph were - $\frac{E}{RT}$ is the slope of the line.

4.3 Results and Discussion

Thermal decomposition.

Figure 4.1 shows the TGA/DTG heating curves of a sample of cassia tora pellet, sample weight 6.438 mg, to 900^oC in air atmosphere. The first weight loss between ambient and about 135^oC is most likely moisture and perhaps other low molecular weight materials leaving the sample. This represents about 9.2 % of the weight of the total material. The second weight loss is cellulose being oxidized and decomposed by the presence of oxygen and represents about 56.4 % by weight of the total. The third weight loss is the oxidation and decomposition of lignin. The sharp spike in the derivative curve indicates the rapid weight loss resulting from the sample catching fire in the sample pan. The sample temperature is also seen to rise slightly above the programmed temperature confirming this interpretation. Above about 550°C further weight loss of about 1 % takes place. This is possibly carbonized material oxidizing. The residue at 800°C is 4.2 % ash and is almost certainly inorganic in nature.

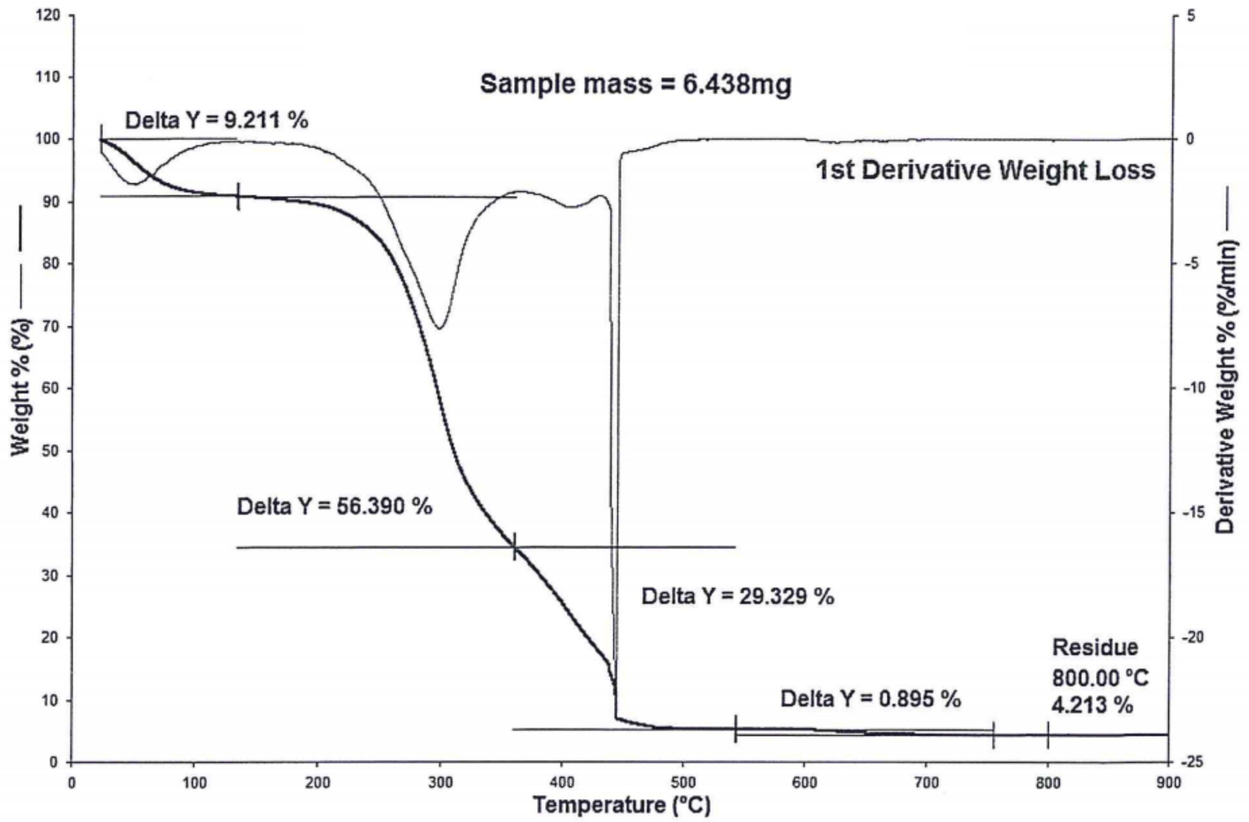


Figure 4.1: TGA and DTG graph of cassia tora stem pellet at 10°C/min heating rate

The coats-Redfern method

From equation 4.6, $ln[\frac{1}{wo-wf}.\frac{dw}{dt}] = ln\,A - \frac{E}{RT} + nln[\frac{w-wf}{wo-wf}]$ and modifying it into Krevlin equation and taking n to be unity then rearranging will give;

$$ln\frac{1}{wo-wf}.\frac{dw}{dt}[\frac{w-wf}{wo-wf}] = ln\,A - \frac{E}{RT} \qquad 4.7$$

$ln\frac{1}{wo-wf}.\frac{dw}{dt}$ is determined from the TGA curve as the derivative weight on the vertical axis. Plotting the values against $\frac{1}{T}$ will give a straight line of with the activation energy calculated from the slop (-E/RT). According to Coats-Redfern the process of pyrolysis encompassed three stages (indicated on the curve as delta y). dw/dt is determined for each point in time since the change in mass with time is different in all the stages. For example from figure 4.1 three stages I, II and III corresponding to dw/dt of 0.59, 3.63 and 1.8 mg/min were calculated. In each stage three points were located where the mass, w1, w2 and w3 were determined. From these$ln[\frac{1}{wo-wf}.\frac{dw}{dt}]$ was plotted against $\frac{1}{T}$ and the values used to plot the presented in figures 4.2-4.4.

From the TGA graph:

Sample mass = 6.438

dm/dt varies at points and are selected as given for the 3 steps A_1, A_2 and A_3;

at A_1, 9.211% of 6.48mg , loss weight due to moisture hence, 0.59mg

at A_2, 56.4% of 6.48mg, loss of weight due to cellulose being oxidized hence, 3.63mg

at A_3, 29.329% of 6.48mg, loss of weight due to oxidation and decomposition of lignin hence, 1.8mg.

Taking a point on A_1 for step I

Ma1 initial mass is 6.438mg

Ma2 mass at time t is 5.9314mg

Ma3 final mass is 5.848mg

Takin a point on A_2 for step II

Mb1 initial mass is 6.438mg

Mb2 mass at time t is 2.3mg

Mb3 final mass is 2.21mg

Taking a point on A_3 for step III

Mc1 initial mass is 6.438mg

Mc2 mass at time t is 0.129mg

Mc3 final mass is 0.126mg

Where Ma, Mb and Mc represent the mass of the material at steps I, II and III respectively. Using equation 4.7 and substituting for the values of the mass at steps I, II and III the activation energy and reactivity for the three steps were calculated and presented in table 4.1.

Table 4.1: TGA data results for kinetic parameters of cassia tora pellet at 10°C/min heating rate

Step	Temperature (°K)	Activation energy *Ea* (kJ/mol)	Pre - exponential factor *A* (s^{-1})	R^2
I	408 to 630	72.01	2.83E+17	0.9839
II	630 to 708	106.81	8.6E+04	0.9832
III	708 to 822	88.67	6.5E+03	0.9867

The activation energies for steps I, II and III are 72.01, 106.81 and 88.67 kJ/mol, while the corresponding pre-exponential factors are 1.76E+19, 5.18E+06 and 3.92E+5 /min respectively. The maximum weight loss occurs at the temperature range of 630 to 708°K and when compared to results obtained in the literature, Rajeswara and Sharma, (1997) reported a maximum weight loss at 573 to 723°K , Mansaray and Ghali, (1999) found out that 740 °K is the maximum weight loss temperature for rice husk. Therefore the actual thermal deterioration of the pellets takes place at step II and final breakdown of the remains at step III as stated in the TGA analysis.

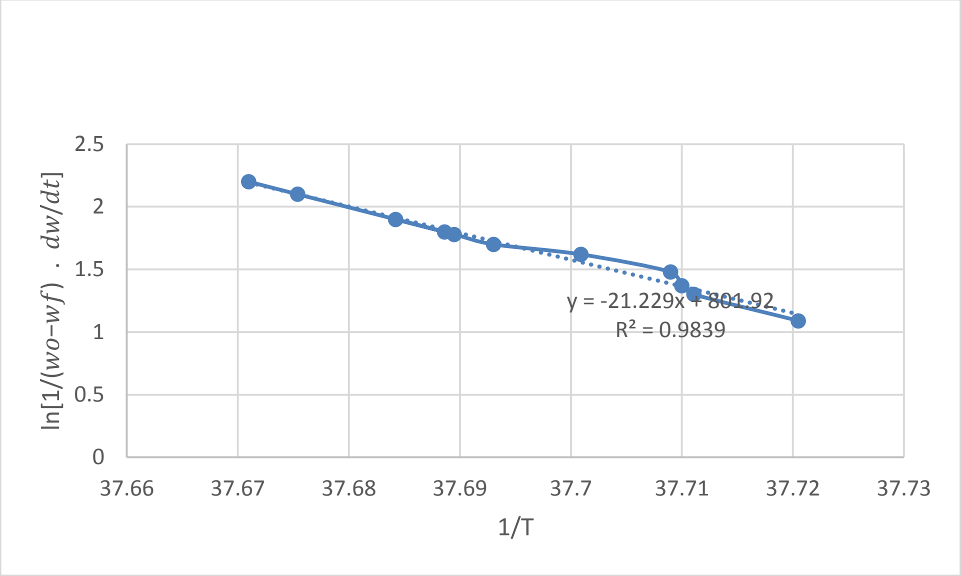


Figure 4.2: Graph of $ln[\frac{1}{wo-wf} . \frac{dw}{dt}]$ against *1/T*(K^{-1}) for TGA/DTG step I at $10^{o}C$/min heating rate

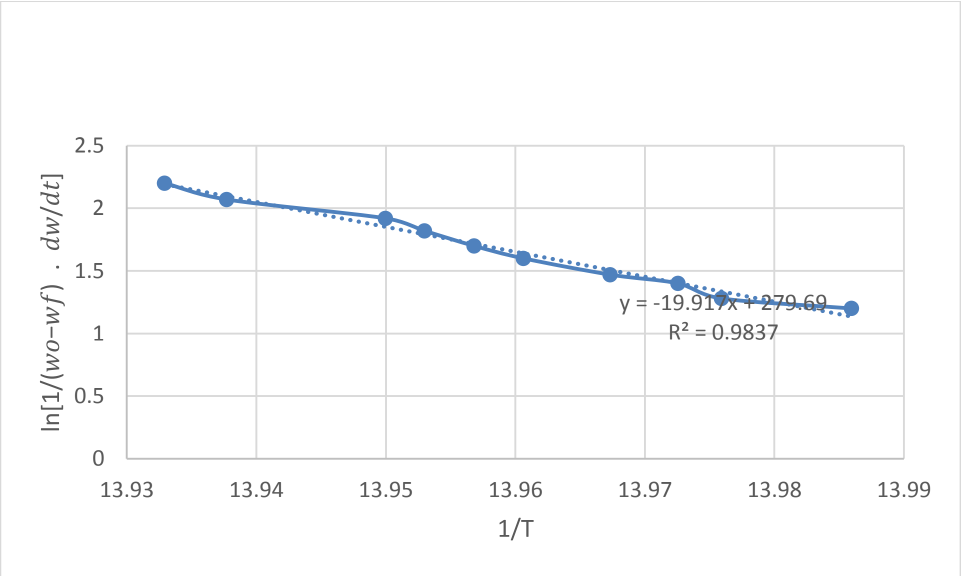


Figure 4.3: Graph of $ln[\frac{1}{wo-wf} . \frac{dw}{dt}]$ against 1/T(K^{-1}) for TGA/DTG step II at $10^{o}C$/min heating rate

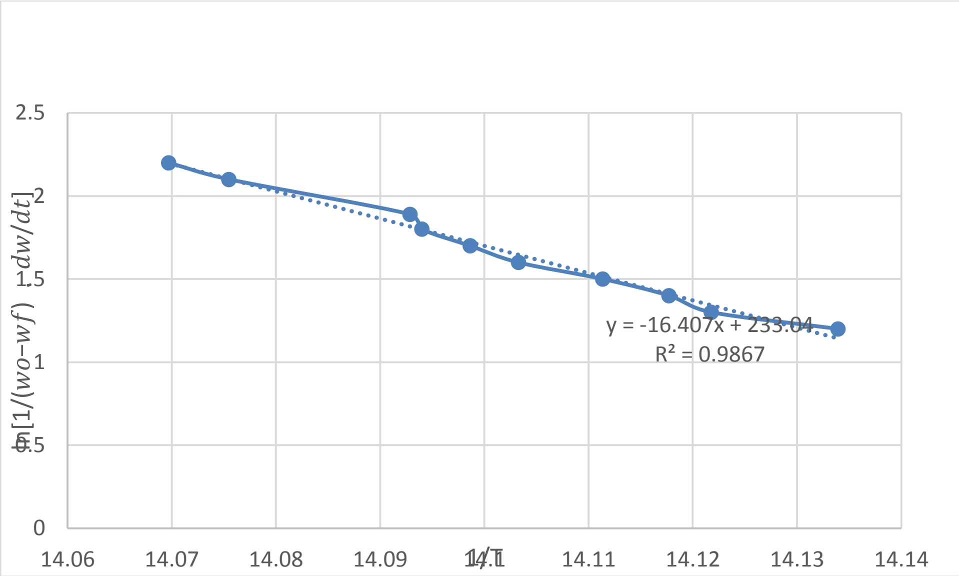


Figure 4.4: Graph of $ln[\frac{1}{wo-wf} \cdot \frac{dw}{dt}]$ against 1/T (K^{-1}) for TG/DTG step III at 10°C/min heating rate

Similar results were obtained by Vuthaluru (2004), for coal/blended biomass activation energies. He found that the values were in the range 46.9-183.6 kJ/mol with the corresponding reactivities of 1.54E+3 to 4.86E+12 /min. Ella *et al*. (2004) also reported activation energies of 96 and 147 kJ/mol for wood. The activation energies for steps I, II and III for rice husk was recorded as 55.05, 84.13 and 21.18 kJ/mol, while for sawdust and wheat husk they were 32.10, 62.29 and 6.52 kJ/mol, and 28.60, 60.14 and (28.09 kJ/mol, respectively. Though different methods have been used in determining the activation energy it was observed that the second stage activation energy of most materials investigated (Han and Kim, 2009; Ella et al., 2004) is highest and this is the stage where the degradation of hemicellulose-cellulose in the biomass sample occurs. The first stage is the dehydration stage where the moisture content of the biomass escapes. Gao (2004) at a heating rate of 10^{o}C /min observed the activation energy of the untreated wood was found to be 126 kJ/mol and for the treated 74 kJ/mol. With what is obtained from the literature the kinematic parameters for the pellets are comparable to other biomass fuels.

4.4. Conclusion

In this work, the kinetics of the thermal decomposition of cassia tora pellets was determined at different heating rates. The pyrolysis process of the pellets includes; dehydration (9.221 %), devolatisation of cellulose (56.39 %), and further devolatisation of lignin (29.329 %). The main pyrolysis process occurred at about 408 to 823^{o}K. Activation energy and reactivity were calculated using Coats-Redfern method and 72.01, 106.81 and 99.67 kJ/mol for steps I, II and III, respectively was obtained. The kinetic parameters of the pellet are comparable to other biomass fuels.

5. PELLET AGEING TRIAL AND EVALUATION OF COOKING ENERGY EFFICIENCY

5.1 Introduction

The use of cassia tora stem pellets may involve the storage of the fuel pellets for both short and long periods. Its potential use in combustion systems may also be continuous which would make demand high and thus the need for storage to ensure a regular supply. Storage of biomass fuels can result in a variation in temperature of the pile content (White and Decuca, 1988, 1978), dry matter losses (Hunke, 1988), fungus growth (Jirjis 1989) and moisture content (Nurmi, 1999; Hunke, 1988). According to Casil *et al.,(*2010) the outside storage of pile wood chips over a one year period caused a slight deterioration of the biomass over the first three months of storage, while it remained unaltered for longer periods of time. Also there was an increase in carbon content and a lower heating value and the oxygen content also increased slightly.

Although there is research information available on the effect of production conditions and storage on the properties of pellets, these were mainly conducted in reference to particular raw materials and there is no available research concerned with investigating these effects with respect to cassia tora pellets. The properties of cassia tora pellets like other biomass materials reported in the literature can therefore change when stored, making it important to investigate these changes for proper understanding and applicability.

It has been highlighted in Chapter 1 that an energy crisis exists in Nigeria, especially in the domestic sector, and thereby households have been forced to mostly adapt traditional fuelwood for domestic cooking. Water boiling experiment was conducted with the aim of investigating the cooking energy efficiency of pellets compared to kerosene, LPG and fuel wood.

The aim of this Chapter is to provide details of an investigation into the effects of storage (six months) on the chemical properties of the pellets and also to evaluate the cooking energy cost and efficiencies of the pellet, fuel wood, LPG and kerosene.

5.2 Materials and Methods

5.2.1 Influence of process parameters and storage

Cassia tora stem pellets were produced under different temperature and pressure conditions as described in Chapter 3. Pellets produced at 50 MPa/30^{o}C and 140 MPa/120^{o}C were collected, weighed, bagged and sealed in woven sacks in July 2013 and stored indoors in the laboratory of mechanical engineering department, Kano state polytechnic. The pellets were kept for six months without tempering under the atmospheric conditions found in Kano state, between July and December. The stored pellets were collected from storage and weighed in December 2013. Proximate and ultimate analyses of the stored pellets were conducted before and after storage. The calorific values of the stored pellets were also determined using a bomb calorimeter. The produced pellets before storage and after storage were also studied using a Zeiss EVO50EVP environmental scanning electron microscope (SEM), fitted with a tungsten filament cathode to provide the electron beam, Fig. 5.1. The SEM is interfaced with an Oxford Instruments INCA energy dispersive x-ray spectrometer (EDS).

Figure 5.1. Zeiss EVO50EVP environmental scanning electron microscope.

5.2.2 Ultimate analysis

The main chemical elements in carbonaceous solid materials (apart from associated mineral matter) are Carbon (C), Oxygen (O), hydrogen (H), nitrogen (N) and sulphur (S). The chemical analysis is very important in calculating material balance accurately and calorific value of the pellet. The C, H, N, and O values were determined for pellets produced at 50 MPa/30^{o}C and 140 MPa/120^{o}C before and after storage period of six months.

i. Determination of C, H and N

The content of C, H, N were determined at Warwick analytical service laboratory by elemental microanalysis (ISO 17025 UKAS: 2005) and expressed on a moisture free basis as specified by CEN/TS 15104 standard. This consist of combustion of the sample pellet followed by separation using gas chromatography. The elements were then detected by an elementary analyser.

ii. Determination of S

This was also determined by Warwick analytical services using oxygen flask method. It consisted of combustion procedure followed by titrimetric determination. The combustion of the sample in oxygen yielded water-soluble inorganic products, percentage Sulphur was determined by titration with barium perchlorate using Thorin screened with methylene blue indicator.

iii. Determination of O

Oxygen was determined by difference according to the following equation,

$$O\ \% = 100 - (\%\ C + \%\ H + \%\ N + \%\ S) \qquad 3.6$$

Where % C, % H, % N and % S are the percentages by weight of carbon, hydrogen, nitrogen and sulphur as determine in 3.2.4 c.

d) Determination of K, Cu, Zn, As, Cr, Pb and Cd (CEN/TS 15290/97)

5.2.3 Determination of elemental composition of the pellets

These were determined by atomic adsorption spectrometry and inductive coupled plasma mass spectrometry (ICP-MS).

In ICP-MS the solid sample was dissolved below 0.2 % to allow for routine operation and maximum stability. The argon inductive coupled plasma generates a single charged ions from the elemental species within the sample which are directed into the mass spectrometer and separated according to their mass to charge ratio. A detector is located where the irons of the selected mass to charge ration are directed. This detector determines the number of ions present.

5.2.4 Scanning electron microscope, SEM.

An SEM uses a beam of high energy electrons to generate a variety of signals through beam-specimen interaction. The signals derived from this interaction reveal information about the sample including external morphology and chemical composition. The signal data is collected over a selected area of the surface of the sample to generate an image.

The SEM electron beam causes low energy secondary electrons (SE) and higher energy back-scattered electrons (BSE) to be emitted from the specimen and these are collected via detectors and the 'signals' used to form the image on a TV screen. The SE electron signal provides better resolution as SEs are abundant, whereas the BSE signal provides more contrast and may give more information on elemental and density differences in a sample. The electron signals are a result of interactions of the electron beam with atoms at or near the surface of the sample. Due to the very narrow electron beam, SEM micrographs have a large depth of field yielding a characteristic three-dimensional appearance useful for understanding the surface topography of a sample.

Beam-specimen interaction also results in the generation of characteristic X-rays. The electron beam removes inner shell electrons from the sample atoms and this causes a higher-energy electron to fill the vacancy in the lower energy inner shell and release energy in the form of an x-ray photon of specific energy. Hence the characteristic X-rays are used to identify the elements present and the overall composition.

5.2.5 Sample preparation, scanning and imaging.

The sample of cassia tora stem pellets were crushed and dried to avoid moisture vaporisation in the vacuum of the SEM. The sample was mounted on a stub and coated with gold to avoid 'charging-up' during scanning by the electron beam. The beam passes through pairs of scanning coils or deflector plates in the electron column, which deflects the focused beam in the X and Y axes so that scanning is achieved in a raster fashion over a rectangular area of the sample surface.

5.2.6 Ageing trial weather conditions

The pellets were stored between July and December, 2013 under conditions found in Kano state, Nigeria.

Although there was no physical tempering of the stored pellets for the storage period, the environmental conditions changed (temperature and relative humidity) during the period of storage. The environmental conditions of Kano state are presented in Figures 5.2

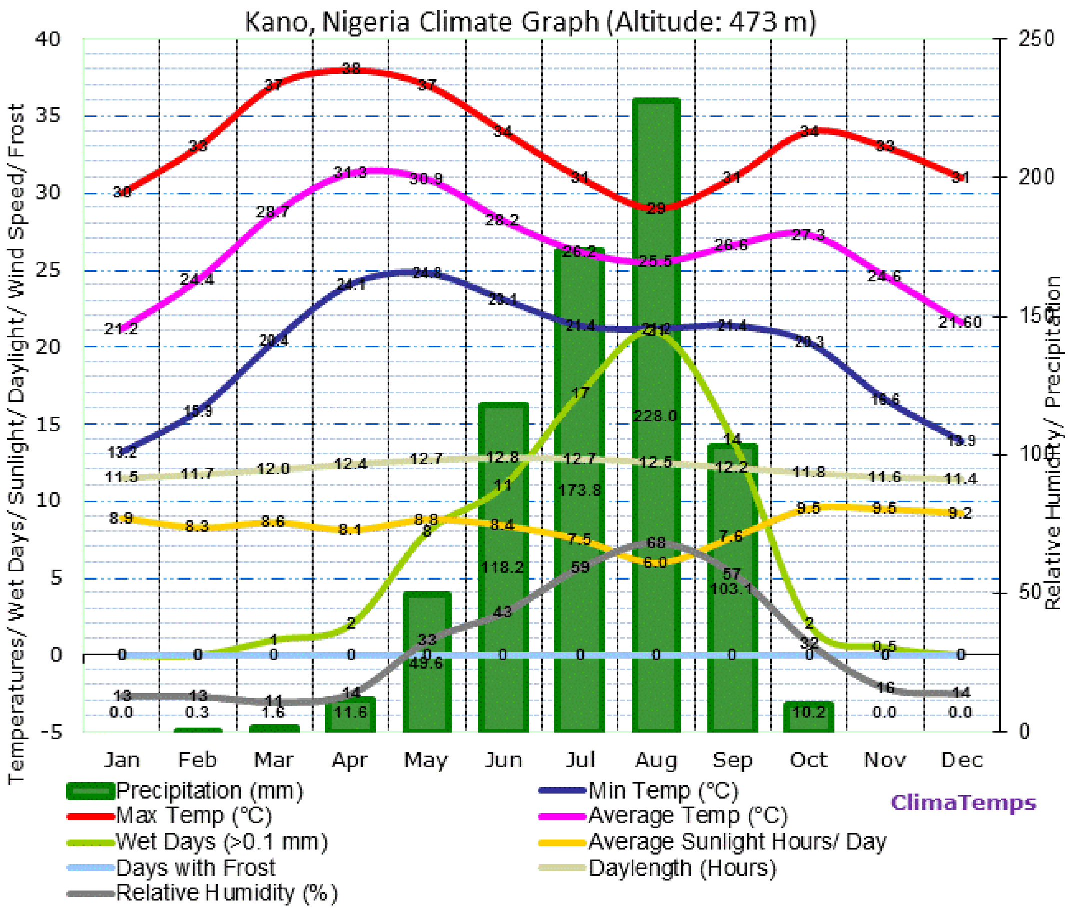


Figure 5.2: Climatic conditions of Kano state, Nigeria

Source: www.ano.climate.com

From Figures 5.2 the climatic condition of Kano state during the storage period shows that the sunshine hours and temperature have a slight variation between July and December, while rainfall is experienced in July to September, October to December is a totally dry period. Humidity is generally high between July and October reaching a peak of about 80 percent in August. Wind speed was averagely uniform during the storage period. The stored pellets were exposed to these climate changes and the condition might have effect on its properties.

5.2.5 Water boiling experiment.

The water boiling test was carried out with freshly produced pellets and was not compared with that of the ageing pellets trial pellets.

A measuring cylinder was used to measure 2.5 liters (approximately 2.5 kg) of water and poured into an aluminium pot. The initial temperature of the water was measured using a thermometer in each case. A charcoal stove was used for the fuel wood and pellets and kerosene stove was used for the kerosene burning experiment, while a 3.9 kg LPG gas cylinder was used and the weight before and after the boiling experiment recorded. The charcoal stove is a locally fabricated metal stove with upper part like a pentagonal frustum attached to the lower part of rectangular cuboid in shape (see figures 3.4 and 3.5). The pellets are put on a mesh in frustum like upper part to allow for air circulation during combustion. The kerosene stove is cylindrical in nature and the kerosene is located at the buttom of the stove where cotton material is made to soak and allow the flow of the liquid kerosene during combustion (figure 5.5).

The masses of fuelwood, pellets, kerosene and LPG were taken and recorded before combustion and after combustion. For the fuelwood and pellets, the mass of each fuel was weighed before the experiment and the remains of the unburnt solid mass of each of the fuels was weighed after the experiment. The quantity of water evaporated after boiling was determined by subtracting the mass of water remaining from the initial mass of water. The experiment was repeated twice for each fuel and average values were used in the computation boiling thermal efficiencies of the fuels. The boiling pot was without a lid and all experiments were conducted at room temperature at the start of each test. The experimental procedure used is in accordance to VITA, (1982) standards.

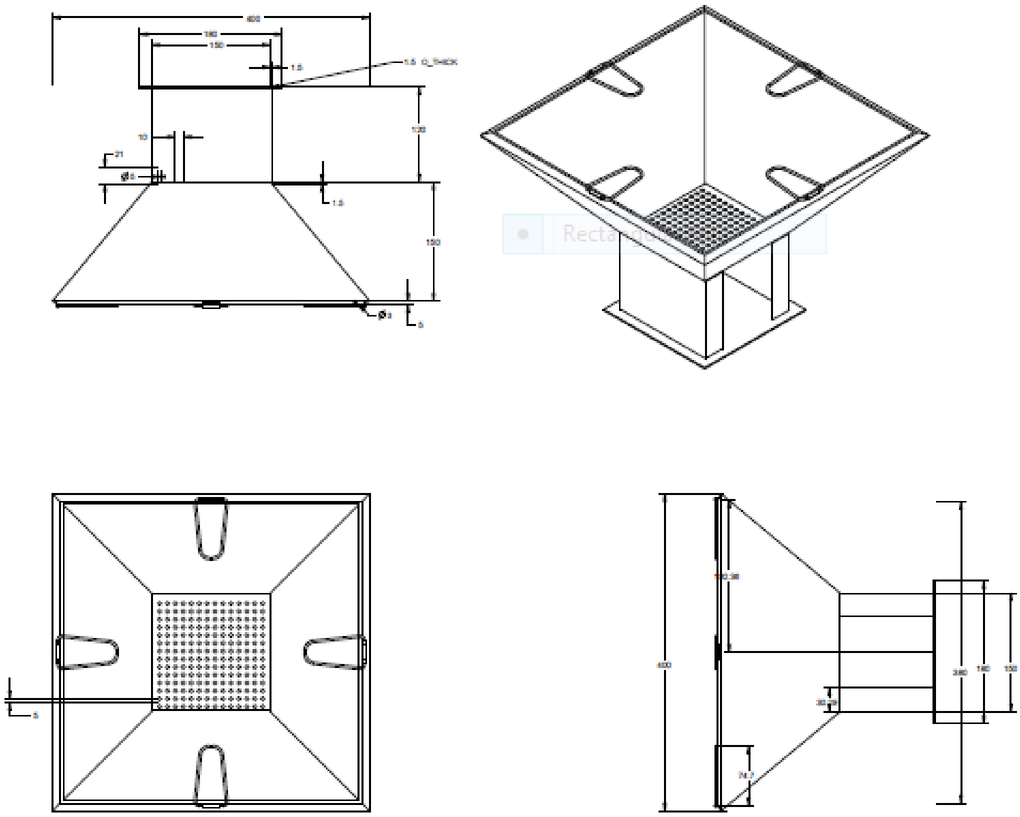


Figure 5.3: Orthographic view of the charcoal stove

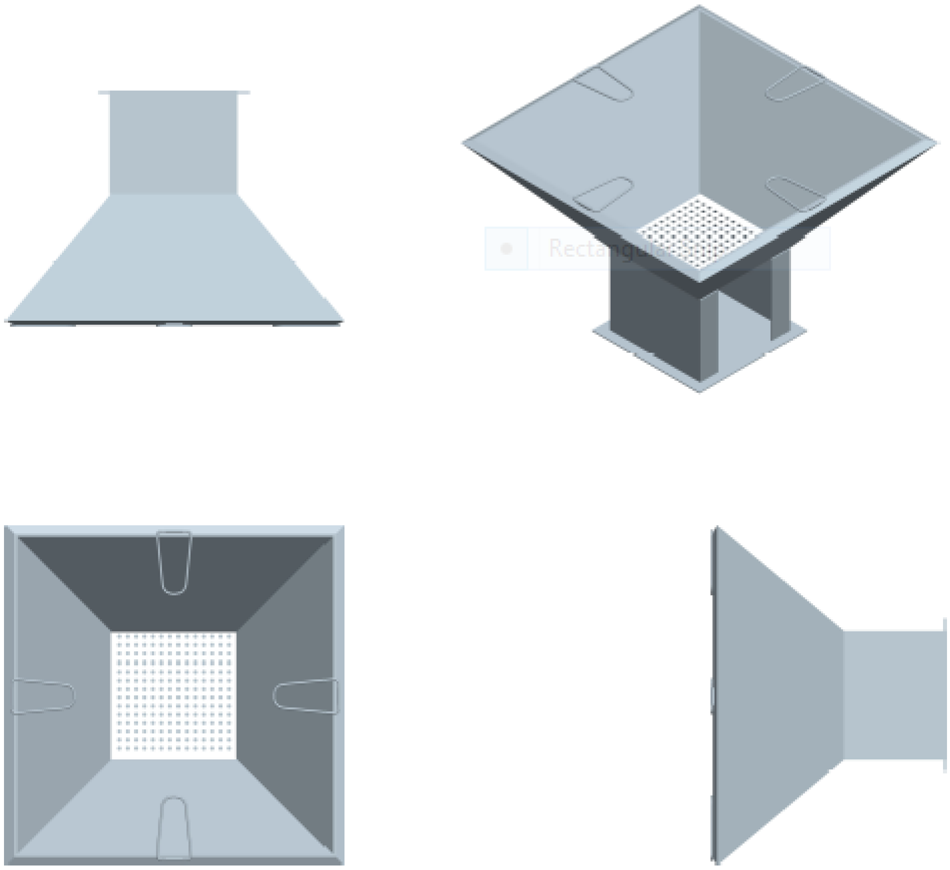


Figure 5.4: Isometric views of the charcoal stove

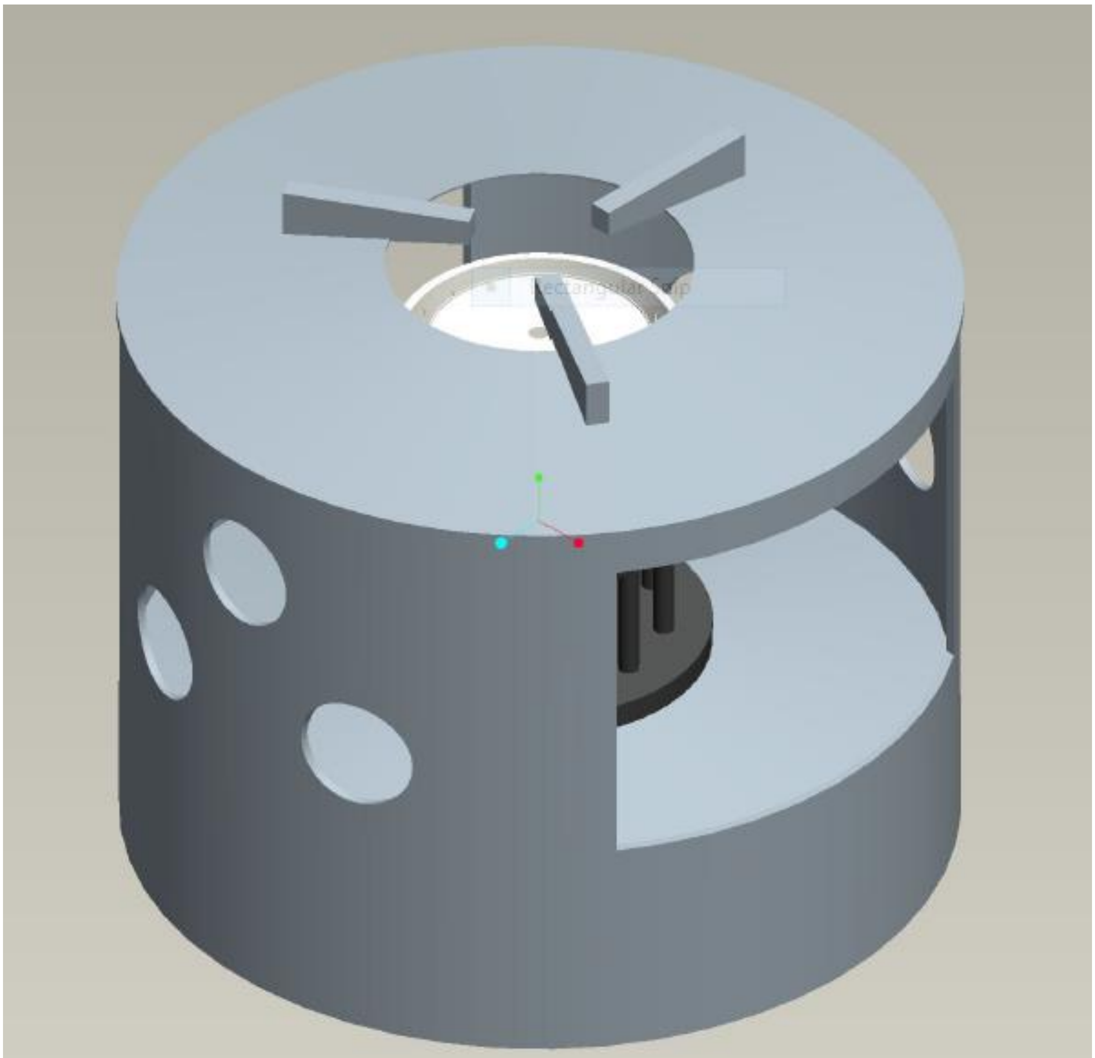


Figure 5.5: Solid drawing of the kerosene stove.

Thermal efficiency

The thermal efficiency for water boiling was calculated by employing the equation used by Anozie *et al*., (2007):

$$\eta\ (\%) = (M_w C_p\ (T_b - T_o) + M_c L) 100 / M_f\ \xi_f \qquad 5.1$$

Where η is the thermal efficiency, M_w is the mass of water (kg), C_p is the specific heat capacity of water at constant pressure (J/kgK), T_b is the boiling temperature, T_o is the initial water temperature, M_c is the mass of water evaporated (kg), L is the latent heat of vapourisation of water (kJ/kg), M_f is the mass of fuel burnt and ξ_f the caloric value of the fuel. Also a correction can be made when the fuel does not burn completely, where,

$$M_f = (\text{initial mass of fuel} - \text{mass of unburnt fuel}) \qquad 5.2$$

5.3 Results and discussion

5.3.1 C, H and N compositions

The carbon, hydrogen and nitrogen composition of the cassia tora stem pellets are presented in Table 5.1. The weight (%) composition of C, H and N before storage was 41.51, 5.72 and 1.41, and 41.47, 5.49 and 1.48 for the pellets produced at 50 MPa / 30°C, and 140 MPa / 120°C, respectively. After storage, the C, H and N composition was 42.37, 5.46 and 1.51, and 44.84, 5.58 and 1.52 for the pellets produced at 50 MPa / 30°C, and 140 MPa /

120°C respectively. There is an increase in the carbon and nitrogen contents, while the hydrogen content reduces after the storage period.

The carbon nitrogen ratio (C:N) in a biomass material represents the nutrients available in the biomass that can be used for biological growth and as a result decompose in a process similar to composting (Summers *et al.,* 2003). The C:N ratio of the pellets before storage is 29.08 and 28.02 for 50 MPa / 30^{o}C, and 140 MPa / 120^{o}C respectively, and after storage 28.06 and 29.5 for 50 MPa / 30^{o}C, and 140 MPa / 120^{o}C respectively. Comparing these values show a decrease in C:N ratio after storage with respect to the pellets produced at low temperature/pressure while there is an increase in C:N ratio with respect to pellets produced at higher temperature/pressure. This indicates that the high moisture content associated with low temperature/pressure produced pellets gives room for biological growth and decomposition in the pellets. Therefore the nutrient content of the pellets reduces after storage.

Table 5.1: Variation of elemental composition with storage for cassia tora stem pellets as a % of dry fuel.

Element	$P_{50,30}$	$P_{140,120}$	$P_{50,30(S6)}$	$P_{140,120(S6)}$
C	41.51	41.47	42.37	44.84
H	5.72	5.49	5.46	5.58
N	1.41	1.48	1.51	1.52
S	0.17	0.21	0.19	0.27
O*	51.19	51.35	50.47	47.79
Cl	0.42	0.56	0.48	0.59
K	0.32	0.39	0.39	0.43
Cd	0.0012	0.0013	0.0023	0.002
Pb	0.0012	0.0013	0.0017	0.0013
Zn	0.004	0.003	0.001	0.003
Cr	0.001	0.001	0.0008	0.001
Cu	0.005	0.005	0.0042	0.0032

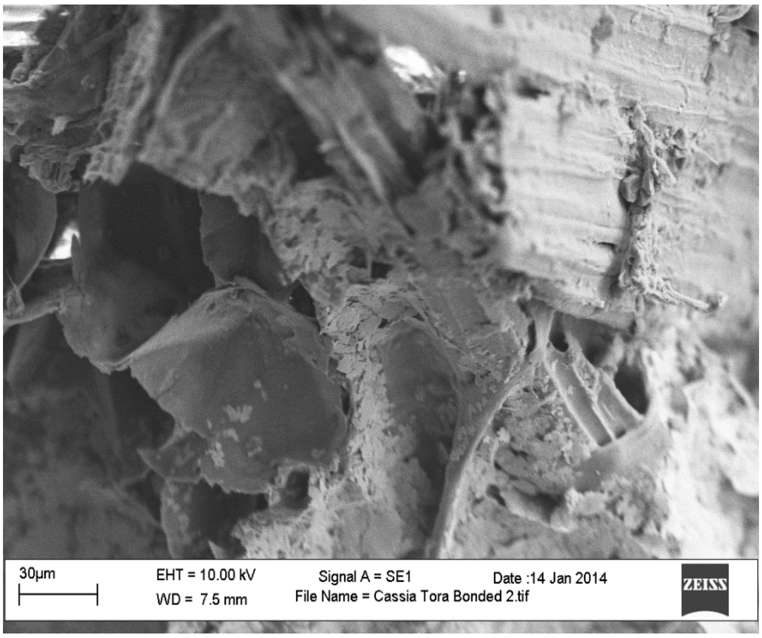
Nomenclature Px,y refers to pellets produced at *x* pressure and *y* temperature; *Px,y(S6)* refers to pellets produced at *x* pressure and *y* temperature and stored for 6 months. * determined by difference

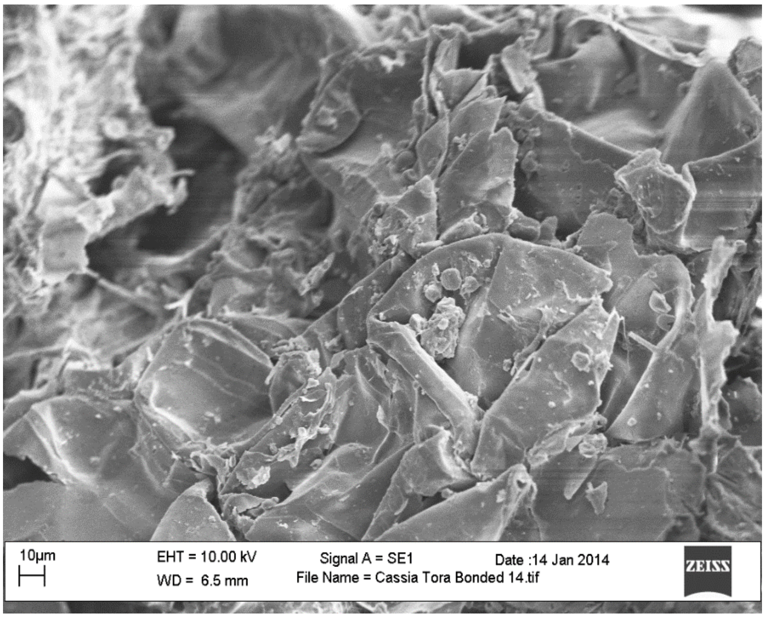
5.3.2 Composition of O, Cl, K, Cd, Pb, Zn, Cr and Cu

From Table 5.1, the composition of oxygen reduces and sulphur increases with storage in each production condition. The elements Cl, K, Cd and Pb increased after storage. Although the percentage composition of Zn, Cr and Cu is very minimal, there is a decrease of each of the elements after the pellets were stored.

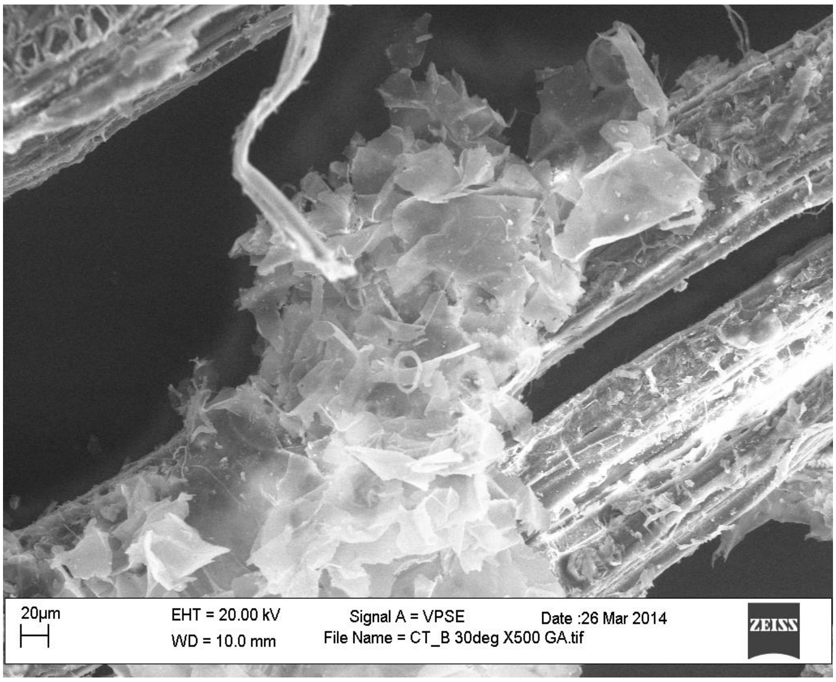
5.3.3 Scanning electron microscope (SEM)

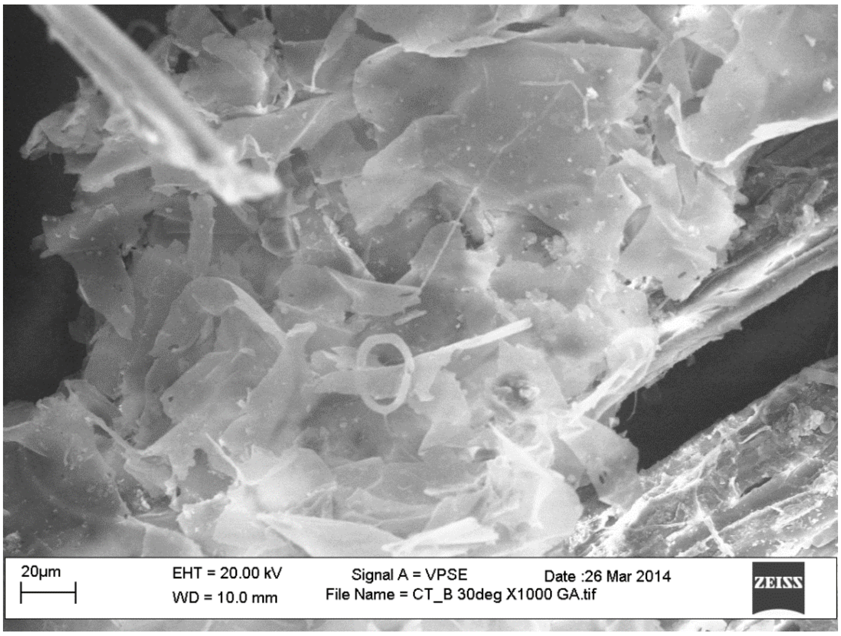
The SEM images for the Cassia tora stem pellets before storage in January 2014 are shown in figures 5.1.7 to 5.1.9. The microscopic interpretation of the pellet structure by Pietsch (2002) was used to describe the binding mechanism of the pellet before and after storage. The SEM image of the binder used (gum arabic) is presented in figure 5.2.5 and 5.2.6 where classic cleavage steps associated with brittle fracture can be seen. The binder when mixed with the cassia tora stem to form the pellets covered the particle to reveal its glassy image. In both cases of the images before and after storage the binder dominates the visibility of the structures. This made it difficult to identify any differences in the case of the pellets before and after storage.



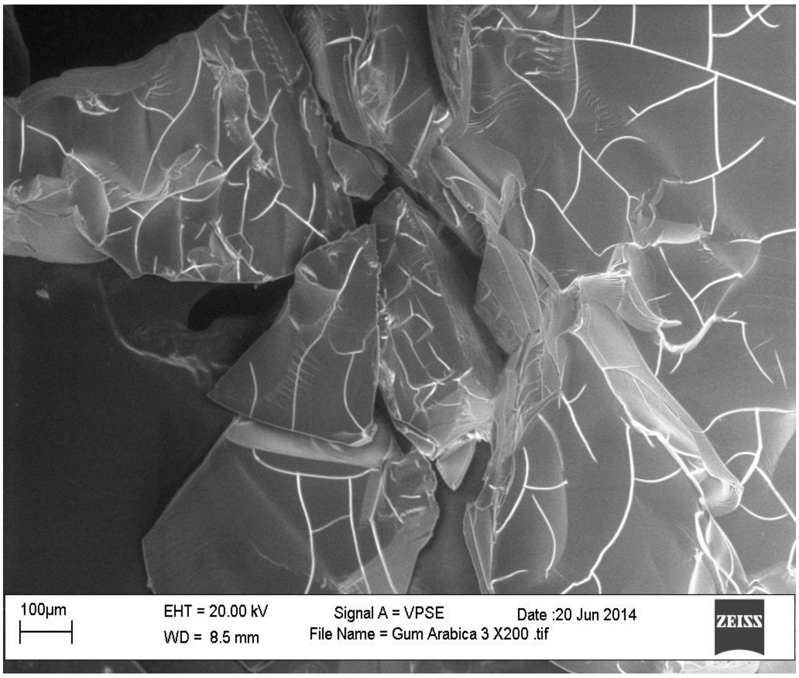


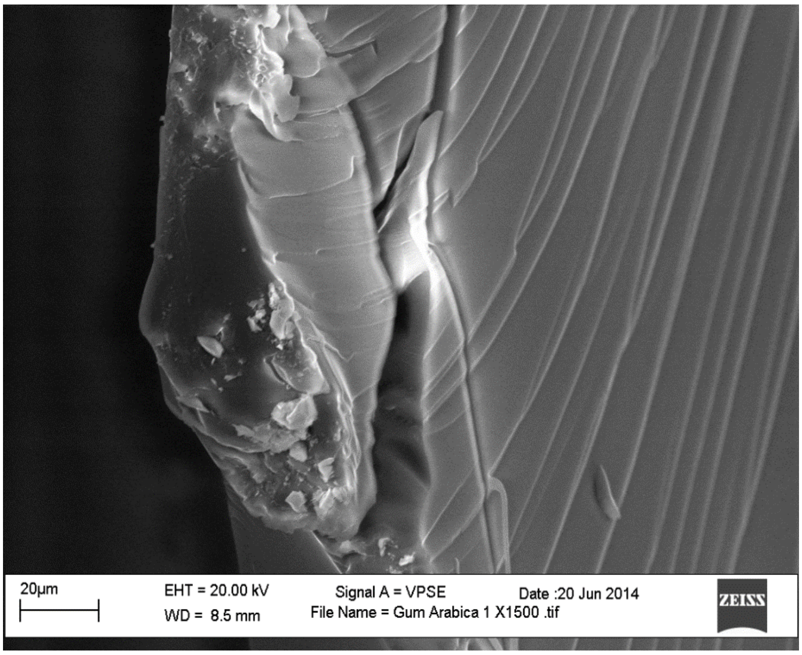
Figures 5.6 a and b: SEM images of cassia tora stem pellets produced in January 2014





Figures 5.7 a and b: SEM images of cassia tora stem pellets produced in March 2014





Figures 5.8 a and b: SEM image of gum Arabic.

5.3.5 Water boiling experiment

Table 5.3 shows the energy consumption and cost analysis of boiling 2.5 l of water. The energy cost of boiling water is 0.2, 0.7, 0.4 and 0.2 Naira (at 250 Naira to 1GBP) with fuelwood, kerosene stove, gas cooker and pellets respectively. It was cheaper to boil water with fuelwood and pellets than with kerosene and gas, with kerosene being the most expensive. In terms of convenience in handling and utilisation, kerosene stove and gas cooker are more convenient followed by the pellets and fuel wood as least convenient. The inconvenience in utilizing the pellets could be due to non-availability of convenient pellet stove and/or other advanced pellet (automated) heating systems, of course not presently available in Nigeria as there is no fuel pellet production for commercial purposes in the country.

5.3.6 Cooking energy efficiency

i. Thermal energy efficiency of water boiling

The energy consumption efficiency (table 5.3) for boiling 2.5 liter of water in a covered aluminium pot was estimated at 32 %, 45 %, 63 % and 31 % for fuelwood, kerosene, gas and pellets respectively. It was observed that the energy consumption efficiency of fuelwood burning is just about the same as that of the pellets and the two were more exposed to atmospheric interference (heat evacuation by air during burning) as the fuels were burnt in open stoves. Other factors that can affect the efficiencies of fuelwood/pellets cooking are moisture content of the fuel, rate of heating and the thickness of the material used in constructing the pot as observed by Bhattacharya *et al.* (2002).

Table 5.2: Energy intensities and cost of selected household fuels

Energy source	M_f (g)[a]	time of boiling (min)	M_c (g)	energy consumed (kJ)[b]	Rate of heating (kJ/s)	Energy intensity (kJ/g water)	Energy cost (*N*)[c]
Fuelwood	185	42	117	3,032.15	1.2	1.2	0.2
Kerosene	45	21	93	1939.5	1.53	0.78	0.7
LPG (gas)	30	15	87	1389	1.54	0.56	0.4
Cassia tora pellets	158	38	122	2859.8	1.5	1.36	0.2

a- Mass of fuel wood used was 430 g the remaining mass of charcoal after water boiling was subtracted from initial mass to obtain mass burnt. Pellets completely burnt into ashes.
b- Calorific values of wood, kerosene and LPG were acquired from average values computed from: biomass energy data book, (2011) and that of pellet from values determined in Chapter 3
c- Computed from values presented in Yekini, (2011)

ii. Energy intensity

The energy intensity of the pellet is higher than that of the remaining fuels. Although more energy was consumed when fuel wood was used in boiling water its low calorific compared to the other fuels makes it less intensive in heating. The result of the energy intensity experiment could be used as a yard stick for comparative ranking of energy consumption efficiency of these household fuels. It was also observed that the rate of heating affects the energy intensity, with a lower rate of heating giving lower energy intensity and high rate of heating corresponding to high energy intensity of the individual fuels.

Table 5.3: Thermal efficiency of water boiling of selected household fuels

Energy source	$\mathcal{E}_f$ (MJ/kg)	initial temp°C	final temp°C	$M_{w\,(g)}$	η (%)
Fuelwood	14.9	18	100	2500	32
Kerosene	43.1	19	100	2500	45
Gas	46.3	18	100	2500	63
Cassia tora pellets	18.1	18	100	2500	31

5.3.6 Application in a Stirling engine

The use of pellets in Stirling engine in Nigeria can help support local industries and households with the provision of electricity. The Stirling engine is a heat engine that operates by cyclic compression of air or other gases (working fluid) at different temperatures, such that there is a net conversion of heat to mechanical work. It is a closed cycle regenerative heat engine with permanent gaseous fluid.

Renewable power applications

The quest for sustainable energy has drawn attention on the Stirling engine's ability to convert a wide variety of heat sources into mechanical work. The Stirling engine is noted for its quite operation and ability to use almost any heat source. Man-made or naturally occurring energy sources are potential resources that could be used in conjunction with a Stirling engine (figure 5.2.7).

Figure 5.9: locally constructed Stirling engine for domestic application

Heat is generated externally rather than by internal combustion as with the Otto cycle or diesel engines. This has made the Stirling engine practically suitable for operation in conjunction with renewable solid fuel pellets for the generation of electricity or production of mechanical energy for water pumping from wells or dams for households, irrigation farming and other benefits. Placing the hot chamber of the Stirling engine in the solid fuel burner (combustion zone) would be an easy way to gather the heat necessary to keep running, as long as the cooling system is maintained. Cassia tora pellets are renewable and clean, with homogeneity in physical and chemical properties and are a suitable fuel for Stirling engines.

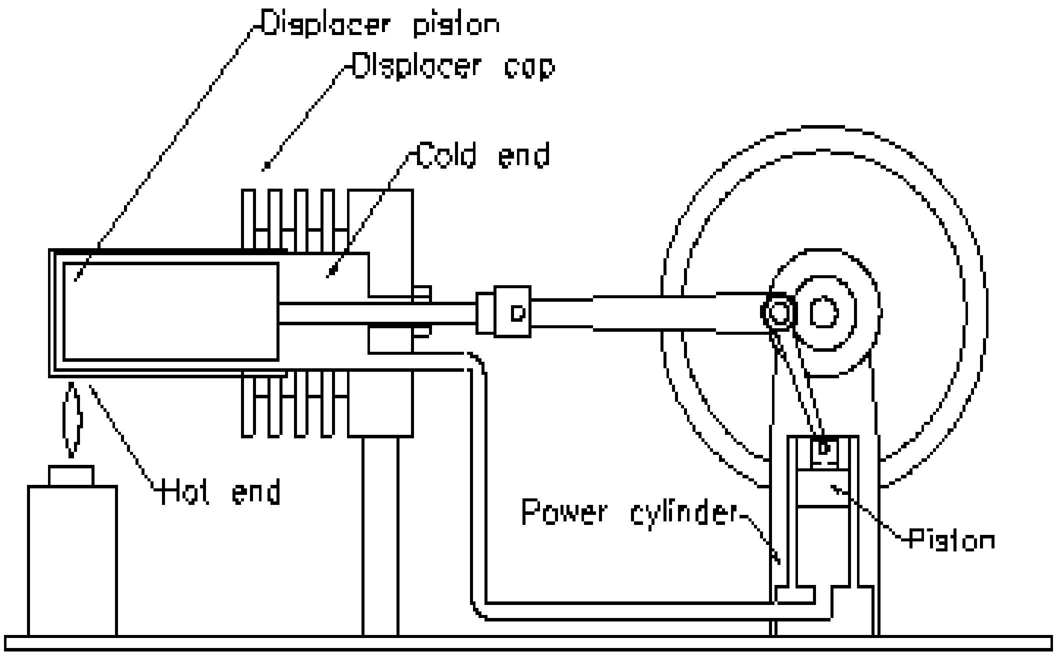


Figure 5.9.1: schematic diagram of a Stirling engine

5.4 Conclusions

The composition of C, H and N of the pellets were found to be affected with storage. There is a decrease in C:N ratio for the lowest production temperature/pressure 30ºC/50 MPa due to presence of moisture than in higher level pellets.

No visible changes were noticed from the SEM images between the pellets before and after storage due to visual dominance of the binder.

Fuel wood and pellets are the least expensive energy sources in Nigeria. Pellet have the highest energy intensity but low thermal efficiency. The energy consumption analysis data from the study could be used with the energy price data, as a guide for investors for the feasibility of investing in fuel pellet production in Nigeria.

6 ECONOMICS OF PRODUCING FUEL PELLETS FROM CASSIA TORA STEMS

6.1 Introduction

Despite all the fortunes the oil sector brings to Nigeria the power sector failed to supply the Nigerian population of over 150 million (CENSUS, 2006) with the adequate energy needed for both industrial and domestic applications. Only about 40% of the households in Nigeria are connected to the National grid (Sambo, 2009), thereby making the majority of the population to be in energy poverty. The situation within the country is that most end users depend on fuelwood for their domestic energy applications. Hence, fuelwood accounts for over 60% of energy supply of the Nigerians living in the rural areas, with over 50 million tonnes consumed annually (Momodu, 2013; UECD/IEA, 2007; Sambo, 2006, 2005). This has resulted in the rate of consumption exceeding the replenishment rate despite various afforestation programs (Anozie *et al.*, 2007). The rate of deforestation was found to be about 350,000 hectares yearly, while the afforestation accounts for 35-40,000 hectares or stands at about 10% of the deforestation each year (International Committee, 2000). Fuelwood for domestic and commercial use, therefore, is the main reason for desertification in the Northern part of the country and soil erosion in the Southern part (Sambo, 2001).

As an energy resource, biomass can be converted into densified fuels in the generation of electricity, heat or fuel for motive power. Biomass resources are considered renewable and its' availability in Nigeria includes, agricultural waste and crop residues, sawdust and wood shavings, animal dung/poultry droppings, and industrial effluents/municipal solid waste (Sambo, 2009).

Agricultural residue can be converted into densified fuel pellets of cylindrical shapes between 12-19 mm diameter and a length corresponding to four times the diameter respectively. Pelletisation as the key technology for converting biomass into densified fuel products to increase biomass use for electricity and heat generation (AEBIOM, 2008). Co-firing energy biomass materials for heat and electricity production can also substantially reduce greenhouse gas (GHG) emission (Styles *et al*., 2008). Many companies around the world are entering into biomass pellet production and markets due to its increasing importance of utilisation for energy purposes (Mani, 2005). Pellets have become a successful internationally traded biomass (Juginger *et al.*, 2008), with plants operating in different countries (Mani *et al., 2006;* Mani, 2005; Obernberger, 2004) to meet household energy needs. More than 1.2 million tonnes of pellets were produced in North America annually (Mani, 2005), which are mostly bagged and marketed for domestic pellet stoves. Pellets were also produced and exported to European countries like, Sweden and Denmark from Canada and North American pellets are utilised for power production in the UK. (Mani, 2006).

Though more than 90 plants have been in operation for biomass pellet production in the US (Hess and Jacobson, 2009; Peksa-Blarchad *et* *al.,*2007), it has proved difficult to obtain reliable information about the cost of production, requirements and market trends for biomass pellets (Anrian et al., 2010). Worldwide, efforts have been performed to identify, compare, model, and calculate production costs of biomass pellets (Chau *et al.*, 2009; Stahl and Wikstrom, 2009; Di Giacomo and Taglieri, 2008; Mahapatra *et al.*, 2007; Mani, 2006; Thek and Obernberger, 2004). Pellet production costs about $78/t and 113$/t in Sweden and Austria respectively (Obernberger, 2004), with raw materials the major contributor to the cost of pellets produced (Mani, 2005).

Though fuel pellet production has gained recognition as an international trade with market size increasing almost annually (Junginger *et al*., 2008; Savalainian, 2007), there is no physical evidence of fuel pellet production in Nigeria, which could contribute to address the issue of insufficient supply of energy for both domestic and industrial applications. Developing countries like Nigeria need to put effort towards fuel pellet production so as to utilise the abundant available resources of biomass raw materials from its' crop residues/waste; this is especially true for the Northern part of the country where the majority population are experiencing a crisis with an inadequate energy supply. To produce cassia tora stem pellets economically a detailed economic analysis, for Kano state in Nigeria, is required considering plant capacity, feed stock, and plant utilisation time.

The objectives discussed in this chapter concern the cost of producing cassia tora pellets and investigating the effect of plant capacity, personnel and production rate on the production cost.

6.2 Economics of production.

6.2.1 Resources of production.

These are the inputs procured (purchased) from the outside and used in the production processes in the making of goods (Paul *et al.*, 2009). Resources of production are classified into groups:

1) Land is an indirect production means which does not directly run production activities but must be available for the placement or locating the human resources and facilities needed or required during the production process.
2) Labour is the human ability, including physical, spiritual and mental ability of an individual worker, with which production activities are performed. An organisation where two or more persons cooperate for a common purpose has a particular importance in most manufacturing systems.
3) Capital is the combination of production objects and direct production means. The production objects are the materials on which activities of production are performed. They consist of,

i. primary materials that are converted into products through the production process such as the raw materials,

ii. auxiliary materials added to the primary materials, e.g. electricity and lubricating oil consumed during the process of production, light and other things supporting the production labour and others.

Direct production means or production facilities are those that directly work on the raw material, e.g. machines, equipment, apparatus, etc. (Paul *et al*.,2009; Stead *et al*., 1996).

6.2.2 Classification of cost

Manufacturing costs are generally classified from two stand points (Hitomi, 1996):

1) Morphological classification
2) Economic classification.

Morphological classification includes;

i) Material cost - occurs by consuming materials.
ii) Labour cost - occurs by utilising human labour force.
iii) Overhead cost- occurs by consuming cost elements other than the above two.

The economic classification includes;

i) Direct cost - incurred directly for producing a piece of the product.
ii) Indirect cost - not directly associated with a particular product.

6.2.3 Selling price

Adding suitable profit to the total cost comprises the selling price.

Selling price = total cost + profit = total cost (1 + Markup rate) 6.1.1

Where, markup rate means the profit against the total cost.

On the other hand, the margin rate is the profit against the selling price.

Margin rate = profit/selling price.

This implies that.

Selling price=total cost / (1- margin rate) 6.1.2

6.2.4 Factors involved in calculating the manufacturing cost

i) Cost estimation; accurate cost estimation, for producing a piece of product, plays a role for capital budgeting. If the product is standardised, or nearly so, the product cost can be easily calculated based on standard cost.

ii) Calculating cost components; value of material necessary for production of a piece of product. This consists of direct material cost, supplementary material cost and indirect labour cost.

iii) Labour cost (personnel cost)

iv) Direct overhead cost (e.g. royalties)

v) Indirect overhead (e.g. insurance, maintenance and electricity)

6.2.5 Evaluation of capital investment

If equipment for which capital was invested produces profits P_j (j = 1, 2, 3,L) over the economic life L in which the facility is capable of operation, the total sum of the present worth of profit is expressed as:

$$P = \sum_{j=1}^{L} Pj/\,(1+r)j \qquad 6.1.3$$

Where, *r* is the average rate of interest or discount (Stead et al.,1999; Hitomi, 1996).

6.3 Materials and methods

A base case scenario of 5t/h pellet production and operating over 210 days annually is assumed in our analysis. Costs associated with crop production, land, machine purchase (imported) and maintenance, offices, transportation and personnel are also considered during the analysis. Secondary data (Anthony *et al*., 2010) was used in the estimation of equipment prices and is presented in tables 6.1 and 6.2. Foreign exchange rate of 1.39 US dollar to 1 Great Britain Pound, 1.27 Euro to 1GBP and 270 Nigerian Naira to 1GBP is used throughout the analysis.

Table 6.1: initial capital cost of equipment for the pellet production plant (base case-8t/h production)

Equipment	Purchase cost (000€)	Installation (000€)	Expected life(yrs)	Capital recovery factor	Annual capital cost (000€)	Specific capital cost (000€)
Grinding plant	405.34	162.14	10	.1424	80.8	1.78
Pelleting & cooling	515.70	273	10	.1424	112.3429.86	2.47
Mis. Elec. Equipment	272	-	15	.1098	1.10	.66
Compressed air plant	9.08	.91	15	.1098	15.68	.02
Packing unit	120	22.8	15	.1098	2,50	.35
Storage bin	20	2.8	15	.1098	13.53	.06
Industrial loader	95	-	10	.1424	13.53	.30
Fork lift truck	11	-	10	.1424	1.57	.03
Office and building	450	-	20	.0944	42.48	.93
land use	200	-	25	.0858	17.16	.38
Total	2098.12	461.97	-		317.01	6.98

Source: Anthony *et al*., (2010)

Table 6.2: operating cost of equipment for pellet production plant

Equipment	Operating cost (€/t)	Maintenance (€/t)	Total cost (€/t)
Grinding plant	7.22	.89	8.11
Pelleting & cooling	7.90	1.13	9.04
Compressed air plant	.10	.05	.16
Packing unit	.30	.05	.35
Storage bin	N/A	.01	.01
Industrial loader	.13	.04	.17
Fork lift truck	.03	.01	.04
Office and building	.18	.20	.38
land use	N/A	.09	.09
Personnel cost	9.31	N/A	9.31
Total	25.17	2.47	27.64

Source: Anthony *et al.*,(2010)

6.4 Pelleting process

Pellets are made by compressing dry ground biomass material under high pressure until the lignin softens and binds the material together sometimes with added binder. The combination of the compression, reduced moisture (usually below 10 percent) and temperature increase gives the pellet a high-volume energy density about three to four times better than that before pelleting.

The process of manufacturing fuel pellets involves the following:

Feed stock grinding

Moisture control

Extrusion

Cooling

Packaging

Feed stock grinding involves standard-sized pellet mills where the biomass is ground to particles that are between two and four mm sieve size. Hummer mills are usually the equipment used in carrying out such operations.

In moisture control, an appropriate moisture level typically less than 10% for most biomass materials is required. Moisture can be removed by oven-drying or by blowing hot air over or through the material particles.

Sometimes the biomass materials are collected dry and moisture can be added by steam injection into the feed stock.

Extrusion is the actual process of creating the fuel pellets. Compression is achieved by use of a roller and heated metal plate (die). The roller is used in compressing the biomass material against the die which includes several holes drilled through it to allow the biomass material to be squeezed through under high temperature and pressure conditions. The biomass material will fuse into a solid mass, thus turning into pellets. A blade is used to slice the pellets into the required length as they leave the die.

When the pellets exit the die and are cut into the required length, they come out at a relatively high temperature. It is therefore, necessary to cool and dry them before they are bagged. This is done by blowing air through the pellets and taking away possible water vapor that can condense and have deleterious effect on pellet storage.

Finally, the fuel pellets are packaged into bags for easy handling in transportation and storage. An overhead hopper and conveyor belt arrangement is used in the bagging of the pellets. (www.ANDRITZ SPROUT; www. California pellet mill company)

6.5 Results and Discussion

6.6.1 Capital cost

The capital cost includes the costs associated with land use, purchase, installation and maintenance of equipment and office building construction. A 13% interest rate was assumed in the cost analysis for dump trucks, front-end loaders and forklifts. Equipment purchase cost was adjusted to 20 % increase from the data obtained from Anthony *et al*. (2010), to give room for inflation. Installation cost of the equipment was also determined at 20 % of the purchase cost taking into account that labour costs less in the Nigeria economic system. The maintenance of equipment and buildings was 2 % capital cost. The pellet and hammer mill have a high repair maintenance cost due to wear and tear hence it was taken as 10 % of the capital cost. A base case scenario of 5 t/h cassia tora pellet is assumed in the analysis.

The total capital cost can be calculated using the equation given by Mani *et al*. (2006);

Total Capital Cost, C_c (N/year) was calculated by:

$$C_c = eC_{eq} \qquad (6.1.4)$$

where e = capital recovery factor

C_{eq} = cost of equipment

The capital recovery factor is calculated using the formula:

$$e=i(1+i)^N/(1+i)^N-1 \qquad (6.1.5)$$

Where i = interest rate (expressed as a decimal), N = lifetime of the equipment (years).

The equipment cost, C_{eq}, was found from the general relationship

$$C_{eq} = \alpha_{eq}P^{neq} \qquad (6.1.6)$$

Where α_{eq} is the unit cost of the equipment (₦), n_{eq} is the scaling factor of the equipment and P is the characteristic parameter of the equipment.

When the cost of equipment for a specific given capacity was unavailable the following equation derived from cost versus capacity relationship was used to determine the equipment cost:

$$C_{eq1} = C_{eq2}(C1/C2)^g \qquad (6.1.7)$$

Where $C1$ and $C2$ = equipment capacity, g = exponent – for process equipment and ranges from 0.4 – 0.8. Previous research (Nolan et al, 2010; Mani et al., 2007) conducted into the economics of producing pellets from woody biomass utilised an exponent value of 0.6 which was also used in this study.

The total cost (capital and operational cost), *CT*, is given by the equation:

$$CT = Cc+C_{op} \qquad (6.1.8)$$

where C_{op} = operating cost (₦ /year)

The final production cost, C_p (₦ /t), for the production of biofuel pellets was calculated from the equation:

$$C_p=CT/t_{op}G_p \qquad (6.1.9)$$

Where: t_{op} = total operational hours of the plant per year (hrs/year)

G_p = production rate (t / h)

The total cost (in Naira and GBP values) associated with the production of the pellets are presented in Tables 6. and 6.4.

6.6.2 Operating cost

The operating costs included are the cost of raw materials, electricity cost and personnel cost. To determine the cost of raw materials as a feed stock for pellet production the following was considered;

- Establishment cost
- Harvest cost
- Storage cost
- Transport cost

Though harvesting has a significant cost influence in biomass feed stock production, it also has an effect on both storage and transport costs depending on the method adopted in harvesting. Establishment cost is avoided in the analysis since cassia tora is assumed to grow as a weed of leguminous crops or in any uncultivated land thus no cost is associated with its establishment.

Storage is usually on the farm before pelleting and is done in the open air or in buildings. Although there is the guarantee of a year’s supply of quality dry feed stock when stored in buildings, cost will increase. However, in the analysis cassia tora is assumed to be harvested and transported immediately to the pellet production site to avoid further cost due to storage.

When transporting non-woody biomass, densification of the biomass in some form is essential to improve bulk density. A local method of packing the dry cassia tora stems was observed where it was packed into a bale like nature (dami in Hausa) to increase bulk density and reduce transportation cost. Although there are standards for transporting goods and other materials in most countries, which is normally based on the cost of fuel, type of transporting material and its load capacity, distance travelled and the weight load to be carried, enquiries and observation resulted in a different pattern of transporting goods in the area concerned. The driver is called upon to assess the goods to be transported and the distance to be covered and the cost is bargained based on the price of fuel at that time. Consultation was made with Kano state Union of Road Transport Workers in order to reach an average cost for load of goods transported over a distance of 5-15 km and assumed within the radius of harvest to pellet production site. Two modes of transport were identified to suit the carriage of cassia tora stems to the pelleting site. These are presented in Table 6.5.

6.6.3 Personnel cost

Personnel costs were included in pellet production, marketing and administration. Going by the Nigerian Minimum Wages System (NMWA, 2011) ₦ 18, 000 is the base for a minimum monthly salary. It was assumed that five people be employed for effective application of labour in pellet production and safeguarding the equipment from theft and vandalisation. If five people are employed for the entire production operation, 1 as a manager on constant morning shift charged with operation and record keepings while 3 are on shift rotation and 1 to serve in bagging and security. A salary of ₦ 18000 plus 10% shift allowance for the 4 staff will give a total of ₦ 79400 monthly. The manger with a basic qualification of at least a diploma in plant operation or related field will collect an average salary of ₦ 45000. An average total monthly salary of ₦ 124400 will result in a rate of ₦ 173/h for a 24h work shift of 7 days per week and taking 4 weeks in a month. For a 5 t/h of pellet production the average estimated personnel cost is ₦ 35/t. Taking cost of electricity in Nigeria at the rate of ₦ 13.16 per kWh.

Taking a base case pellet plant with a production capacity of 5 t/h and an annual production of 32400 t assuming the plant operates for 270 days annually (annual utilisation period of 74 %) the operating and total production cost have been calculated and are presented in Table 6.4.

6.6.4 Total cost

The total cost of production which comprises the capital and operating cost was calculated and also presented in Table 6.6. A total of ₦ 1286.4 (4.755 GBP) was estimated for each tonne (t) of fuel pellet produced. At a profit margin of 20 %, each ton of the fuel pellet will be sold at 1550.0 ₦ /t. Comparing the cost to the values presented in Table 6.8 the cassia tora pellet is cheaper than all the other fuel commodities used by the households. And when compared to the fuel wood it is cheaper and also has a higher heat energy content (see Chapter 3 and 5)

Table 6.3 Summary of initial capital cost (in Naira) of the equipment for the pellet production plant (base case – 5 t/h production rate).

Equipment	Purchase cost (₦ 1000)	Installation cost (₦ 1000)	Expected life (yrs)	Capital recovery factor	Ann. Capital cost (₦ 1000)	Specific capital cost (₦ /t)
Solid fuel burner	28057.2	5611.44	10	0.1295	4360.24	173.026
Rotary drum dryer	70140	14028	15	0.0963	8108.94	321.78
Hammer mill	12024	2404.8	10	0.1295	1868.6	74.15
Pellet mill	63126	12625.2	10	0.1295	9810.13	389.29
Pellet cooler	640.8	128.16	15	0.0963	74.09	2.934
Screen shaker	4809.6	961.2	10	0.1295	747.44	29.66
Packaging unit	16032	3206.4	10	0.1295	2491.46	98.87
Storage bin	2404.8	480.96	20	0.0963	231.56	9.19
Miscellaneous equipments	16833.6	3366.72	10	0.1295	2616.03	103.81
Front end loader	2404.8	0	10	0.1295	311.43	12.36
Fork lifter	16432.8	0	10	0.1295	2128.12	84.45
Dump truck	20040	0	15	0.0963	1930.7	76.62
Office building	8016	0	20	0.0802	643.2246	25.52
Land use	2004	0	25	0.071	142.1887	5.64
Total	262965.6	42813.6			35464.15	1407.31

Source: Author’s computation

Table 6.4 Summary of initial capital cost (in GBP) of the equipment for the pellet production plant (base case – 5 t/h production rate).

Equipment	Purchase cost (1000£)	Installation cost (1000£)	Expected life (yrs)	Capital recovery factor	Ann. Capital cost (1000£)	Specific capital cost (£/t)
Solid fuel burner	103.92	20.78	10	0.1295	16.15	0.64
Rotary drum dryer	259.8	51.96	15	0.0963	30.03	1.19
Hammer mill	44.53	8.91	10	0.1295	6.92	0.27
Pellet mill	233.8	46.76	10	0.1295	36.33	1.44
Pellet cooler	2.37	0.47	15	0.0963	0.27	0.01
Screen shaker	17.81	3.56	10	0.1295	2.77	0.11
Packaging unit	59.38	11.88	10	0.1295	9.23	0.37
Storage bin	8.91	1.78	20	0.0963	0.86	0.03
Miscellaneous equipments	62.35	12.47	10	0.1295	9.69	0.38
Front end loader	8.91	0	10	0.1295	1.15	0.06
Fork lifter	60.86	0	10	0.1295	7.88	0.31
Dump truck	74.22	0	15	0.0963	7.15	0.28
Office building	29.69	0	20	0.0802	2.38	0.09
Land use	7.42	0	25	0.0709	0.53	0.02
Total	973.95	158.57			131.35	5.21

Source: Author's computation

Table 6.5 Estimated transport cost of dry cassia tora stems.

Haulage type	Max. load	N/km/tdm	15km(₦ /tdm)	15km (£/tdm)
Mitsubishi canter	7.5	13.2	356.4	1.32
Articulated unit and chip van	14.5	23.76	198	0.73

Source: Author's computation

Table 6.6 Cost of cassia tora pellet production for a base case of 5t/h production plant.

Pellet process operation	Capital cost (₦ /t)	Operating cost (₦ /t)	Total cost (₦ /t)	Total cost (£/t)	Percentage cost dist.
Raw material	0	198	198	0.73	15.35
Drying operation	0	0	0	0	0
Hammer mill	74.15	29.6	103.75	0.38	7.99
Pellet mill	389.29	155.72	545.01	2.02	42.48
Pellet cooler	2.94	0.059	3	0.01	0.2
Screening	29.66	0.58	30.24	0.11	2.3
Packaging	98.87	1.98	100.85	0.37	7.78
Storage	9.19	0.18	9.37	0.035	0.74
Miscellaneous equipment	208.24	4.16	212.4	0.79	16.61
Personnel cost	0	52	52	0.19	4
Land use	31.16	0.62	31.78	0.12	2.52
Total cost	843.5	442.899	1286.4	4.755	100

Source: Author's computation

Figure 6.1 represents the relationship between, capital, operating and total cost with respect to production rate. The higher the production rate the lower the cost of production. This implies that with an increase in production rate the cost of the fuel pellets will reduce and therefore the total cost of production and the final cost of the fuel pellet per ton.

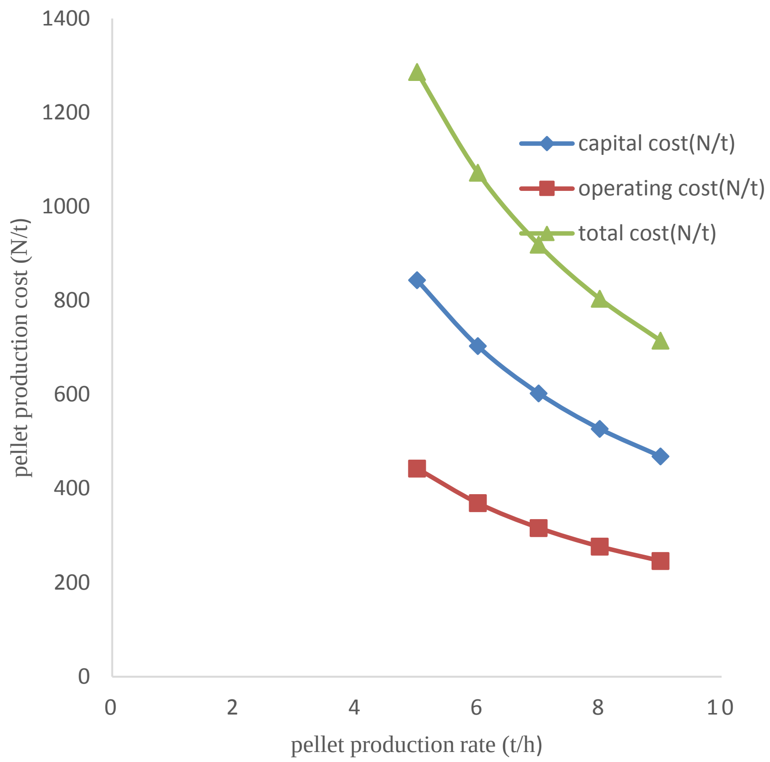


Figure 6.1 Cassia tora stem pellet production vs. production rate.

6.6.5 pay-back period (PBP)

This amount of time that is expected before an investment will be returned in form of income. In the case of cassia tora production scenario the pay-back period is assumed to be an even cash flow investment, where the investment is expected to bring income that is constant each year.

PBP is therefore the cost of investment divided by annual cash flow.

PBP = cost of investment / annual cash flow

Assuming a pay-back period of 15 yrs, the annual profit expected from the capital investment of 35464150 Naira is given by;

35464150 / 15 = 2364276.67 Naira annually.

And for a total production of 32400t annually and if a tonne is sold at1550 Naira,

then, 50000022 Naira will be realized annually. But the production cost is 1286.4 Naira, hence it will amount to about 41679360 Naira. The selling price minus the production cost will give the annual profit of 8320662 Naira. Therefore it is possible to have a pay-back period of less than 15 yrs in this case scenario. Looking at figure 6.1, it is apparent that larger scale production reduces the cost of production which in turn increases the profit and automatically the pay-back period will reduce.

6.7 Conclusion

Cassia tora stem pellets can be economically produced with a total capital cost estimated to be about ₦ 35million or £131,350, a unit capital cost of about ₦ 1094.57/t or £4/t, assuming no cost of raw material occurs and negligible cost of plant drying due to the high-temperature conditions in Kano, state, Nigeria.

The total production cost is ₦ 1286.4/t of the cassia tora pellet. At a profit margin of 30 % the selling price is established at ₦ 1672.32/t. Personnel cost is also considered cheap compared to the pellet production in Europe and America. Scale of the plant has a significant influence on the pellet production cost. Small scaled pellet plants are more expensive to operate, which eventually increases the production cost compared to a larger-scale pellet plant with production capacity greater than 9t/h which produces less-expensive pellets.

Given the current energy prices for kerosene, gas and fuelwood in Kano, cassia tora pellets at base cost with a 30 % profit margin inclusive, could be economically feasible. Though heat energy contents of LPG and kerosene are higher than that of cassia tora pellets, the products' unavailability coupled with high cost has made households dependent on wood fuel.

Substituting cassia tora fuel pellets for fuelwood in domestic applications and cottage industries will therefore, help in reducing the problems of felling of trees (deforestation), desert encroachment, waste stream accumulation, pest housing and soil retardation. Fuel pellet production will also contribute in boosting the economy of Kano state and Northern Nigeria, through employment opportunities for workers, marketers and wholesalers of the product and in addition provide investment opportunities for local and foreign investors. With these factors and the current inadequate supply of energy commodities like kerosene, fuel wood LPG and the problems associated with storage and environmental effects, it is important and economically feasible to produce fuel pellets from cassia tora for domestic and other applications.

7 HOUSEHOLDS' WILLINGNESS TO PAY FOR CASSIA TORA STEM FUEL PELLETS

7.1 Introduction

Willingness to pay (WTP) is an important concept in environmental economics. It is one method that can be used to determine the price of goods, especially where price is not known. Therefore, it is a concept according to Philcox (2007) that defines the amount (measured in goods, services or dollars) an individual is willing to give up for a particular good or service. In economics, WTP represents one of the major alternative means to measure value, and today it is becoming increasingly popular as one of the standard approaches that are used by economists to place a value on goods or services for which no market-based pricing mechanism exists. (Samwel, Isaac and Joel, 2012).

According to Jesdpipat, (2003) WTP is the foundation of the economic theory of value. The idea is, if something is worth having, then it is worth paying for. In theory, according to Letson (2002) economic value of any good or service is measured in terms of what people are WTP for the commodity less what it costs to supply it.

In the absence of physical evidence or available literature showing the existence of production and marketing of fuel pellets as energy products in Nigeria (as stated in Chapter 6), it is therefore necessary to study the valuation of willingness and ability to pay for the new product with regards to cassia tora stem pellets. In recognition of problems of this type, economists have developed a number of non-market valuation methods (Mishrah, 2003; Bateman and Kenneth, 2001) and the principal among them is the contingent valuation (CV) method. According to Mitchell Carson (2005), CVM is a surveyed-based approach developed for determining an individual's WTP for some environmental improvement based on hypothetical market conditions.

Although, many applications of CVM deal with public goods, it is certainly possible to employ the method for commodities available for sale in the market place. It is also evident from the literature that CVM has also been used around the world in policy making (Albenini *et al*., 1997). The Food and Agricultural Organization (FAO, 2003) also reported that both the World bank (WB) and United States Agency for International Development (USAID) have an interest in CVM as a means of assessing demand for goods and services in developing countries.

A critical element in CVM is a questionnaire that is based on a hypothetical description of the good, available substitutes and how it would be paid for (Letson, 2002). This implies that the design of the survey questionnaire is a key element in determining the quality and the quantity of the survey. There is no evidence existing of fuel pellet production and/or no market value for fuel pellets in Nigeria, hence the need to apply CVM in order to determine households' acceptance and WTP for cassia tora pellets.

The study, discussed in this Chapter, covered the Kano metropolis, which consists of eight local government areas with an annual growth of 3.5 % (NPC, 2006) and is considered one of the fastest growing regions in Africa.

The use of cassia tora stem pellets was introduced among some selected households within the metropolis, and the estimated cost of production obtained in chapter 6 was also used in the questionnaire. Some constraints faced during the study were the inability of some households to read or interpret the information in the CVM questionnaire and some respondent's reluctance to cooperate and give information, thinking that the ‘Government’ might use this against them. Nonetheless, these issues were overcome, firstly, through oral interviews and the questionnaire explained more during data collection. Secondly, for those having the fear that Government might use certain information against them, careful explanation convinced them that the research was strictly an academic exercise and had nothing to do with politics.

This chapter presents the analysis of household's WTP for cassia tora stem pellets and it is intended that the chapter will contribute to an improved understanding of energy poverty, and willingness for the general populace to change to an environmentally friendly fuel for their domestic applications in Nigeria, especially the Northwestern part of the country. It is also hoped that the information provided will be useful to policy makers and investors (local and international) in addressing the situation of the energy crisis in Northern Nigeria and for investment opportunities in fuel pellet production respectively.

7.2 Materials and methods

The methodology employed in this chapter involves examination of the background of the study area, the population of the study, the sample size and sample technique, method of data collection and model adopted and techniques of estimation.

7.2.1 The Study Area

Kano is one of the major commercial cities in Nigeria and the largest in Northern Nigeria. According to the 2006 census Kano, state has the highest population of any state in Nigeria, but its metropolitan population is the second largest after Lagos state metropolitan population. The Kano urban area covers 137 km^2, comprising six local government areas, i.e. Fagge, Dala, Gwale, Tarauni and Nassarawa. Kano state is located 480 meters above sea level lying north of the Jos plateau, and located in the Sudan Savannah region that stretches across the south of Sahel. The region features savannah vegetation and a hot semi-arid climate.

Kano state is a commercial and agricultural state with more than 180,684 m^2 of cultivable land and is one of the most extensively irrigated states in the country (www.FGN, Kano state).

Kano state was a great manufacturing state, but the once booming manufacturing sector has stagnated for years due to an inadequate supply of energy/power. Although the present administration has been making efforts to curtail this through independent power projects, utilizing the Tiga and Challawa George dams, the expected outcome is about 35 Megawatts, and this will be used mainly to consolidate water supply and street lighting schemes (www.pointblanknew.com).

Though Kano state is the commercial center of Northern Nigeria, the inadequate supply of energy has hindered the economic development of the state, and this has left the majority of its population living in poverty, especially in rural areas. Most of the residents, both in urban and rural areas, use fire wood and other plant residues for their domestic needs. Hence the need for alternative energy sources that are efficient, cost-effective and more environmentally friendly.

Predominantly, the available energy sources in Kano are kerosene, cooking gas, firewood, maize /millet stalks (*Kara),* and cassia tora stems. Evidence (Fidelis *et al.*, 2014; Ali and Richard, 2013; Audu, 2013; Anozie et al., 2007) has shown that the majority of households are using firewood (6 out of every 10 households) as their domestic energy source followed by kerosene and gas (2 out of 10 households), maize/millet stalks and cassia tora stems (2 out of 10 households).

Households procure cassia tora from their environs and where they cannot do that directly, they buy from vendors who are predominantly children and youths aged up to 18. However, there are no statistics on the volume of cassia tora sold/bought in the state or on the amount of money generated but given its low-cost and availability and of course when densified into pellets, it should prove cost effective because unlike firewood and charcoal that come from other states of the country, cassia tora grows within the state.

7.2.2 Population of the study

The Kano metropolis is today one of the fastest-growing cities in Nigeria and the largest in Northern Nigeria. The population rose from 130,170 in 1952 to 295,432 persons in 1963 (Maiwada, 2000). According to the 1991 population census, Kano metropolis had 1,432,255 persons. However, in 2006 census Kano metropolis has a population of 2,165,233 (Census, 2006). Bayero University Consultancy Unit reports (2012) projected a population of 3,496,180 persons with an estimated population of 318,738 households in Kano metropolis in 2012. The estimated population of the Kano metropolis is presented in Table 7.1.

7.2.3 Sample size and sampling technique

A multi-stage approach to sampling was adopted in order to maximize the benefit of both simple random and stratified sampling methods. The first stage involved identifying various sampling units into a different group (strata) to represent three types of residential class (high, middle and low income residential areas). In each classified residential area, 6 strata were identified.

In the second stage, four areas were randomly selected from the identified strata by a ‘dip and pick’ method with a view to ensuring that each stratum had an equal chance of being included in the sample study, making a total of twelve study areas.

In the third stage, a total of 420 respondents were drawn from selected survey areas within the Kano metropolis, i.e., 120 from respondents in higher-income areas, 140 from the middle-income areas and 160 from the low-income areas. This is presented in Table 7.2.

Table 7.1: Estimated population of Kano metropolis by LGAs in 2012

LGA	Estimated population	Estimated number of
	(March, 2012)	Households
Dala	471083	42826
Fagge	219877	27485
Gwale	488018	48802
Kano municipal	414450	31881
Kumbotso	376517	41835
Nasarawa	740898	52921
Tarauni	271572	30175
Ungogo	513764	42814
Total	3496180	318738

Source: Bayero University Consultancy Unit (2012)

Table 7.2: Stratification of study area

Residential classification	residential area	study area
High-income area	Dorayi(Sabuwar Abuja)	Dorayi(Sabuwar Abuja)
	NNDC quarters	NNDC quarters
	Hotoro GRA	Nassarawa GRA
	Nassarawa GRA	Sani mainagge B
	Bompai GRA	
	Sani mainagge B	
Middle income area	Sani mainagge A	Gwammaja housing estate
	Kabuga (Janbulo)	Dandago by city ice
	Gwammaja housing estate	Rijiyar zaki
	Dandago by city ice	Kabuga (Janbulo)
	Rijiyar zaki	
	Gandun albasa	
Low income area	Aikawa quarters	Aikawa quarters
	Mandawari	Mandawari
	Rimin kebe	Kurna Asabe
	Dakata by tudunwada	Rimin kebe
	Madabo	
	Kurna Asabe	

Source: developed by the researcher, 2014.

7.2.4 Data collection

To obtain demand side information on household's valuation of the cassia tora fuel pellets as a possible substitute to other domestic energy fuel commodities in Kano state, CV was applied. For this purpose, the structured CV questionnaire was administered to 420 randomly selected households from the 6 local government areas within the Kano metropolis. In the process of conducting this research survey, a pre-test study was conducted to further validate the content of the CV questionnaire for reliability. A pre-test is very important for high-quality implementation of CVM, especially for survey data. In the pilot study, a total of forty two questionnaires were administered to two congested suburbs of Kano city, Aikawa and Mandawari. Prior to this, a two day theoretical as well as practical training was conducted for data collection. Although mail, telephone or face-to-face methods are used in CV surveys, it was the face-to-face approach that was used in this survey because it is considered the most controllable and effective method.

In the formal survey, a dichotomous choice contingent valuation method (DC-CVM) was employed because it is more cognitively manageable and more similar to a real buying scenario. In this format, the respondent is offered a binary choice between two alternatives. One which is the present status quo like availability of energy fuel products and the other, an alternative-fuel product that has a greater cost than the status quo (Carson, 2000). The DC-CVM includes three sections; questions related to quality of environment, particularly as related to the energy fuel used, questions closely linked to the WTP and questions used to extract information on the socio-economic background of surveyed households.

7.2.5 Model of households' willingness to pay

The model adopted for in this study, was a valuation function used by Khattak et al., (2009) used to examine WTP for solid Waste Management services in urban areas of district Peshawar, Pakistan. In the model households' WTP was treated as a dependent variable and was regressed on socio-economic variables that included education level, income, household size. This is represented in the equation:

$$WTP_i = \beta_0 + \beta_1 E + \beta_2 I + \beta_3 HH + \beta_4 A + \beta_5 DH + \mu_i \qquad 7.1.1$$

Where *I, H* and *D* represent socio-economic variables and μ_I is error term.

Modifying equation 7.1 and specifying a binary choice model gives

$$Y^* = \beta_0 + \Sigma \beta_i X_{ij} + \mu_I \qquad 7.1.2$$

Where *Y** is the dichotomous independent variable which can assume the value of 1 or 0. It measures the households' WTP which is an unobserved implicit variable. This study conceptualises households' WTP as an actual observed dependent variable defined by:

HWTP = { 1 if the sampled household is willing to pay or 0 if otherwise.

The assumption is households are faced with a choice between two alternatives i.e., they are WTP or they are not. It is also assumed that households' WTP for a new energy fuel product is a function of the following independent variables as shown in the following explicit model to be estimated:

$HWTP = \beta_0 + \beta_1 Age + \beta_2 Edu + \beta_3 Gend + \beta_4 Ocup + \beta_5 FS + \beta_6 EFS + \beta_7 Inc + \mu_I$....7.1.3

Where:

HWTP = household WTP

Age = age of the household

Edu = household educational level

Gend = household gender

Ocup = occupation

Inc = income

FS = family size

EFS = energy fuel supply

μ = error term or random variable.

7.2.6 Technique of Estimation

The study employs both descriptive and inferential statistics in the estimation and analysis of the data collected. Descriptive statistics were used to describe the basic features of data collected, especially socio-economic and demographic attributes of the selected sample households. It was also used to estimate the mean as well as the maximum and minimum amount households are WTP for the newly introduced energy fuel product (cassia tora stem pellets). The descriptive statistics include tables, percentages, means, standard deviations, minimum and maximum values.

The Chi-square test (common test) was the inferential statistic technique employed to test for the significance of the data collected in relation to households' WTP. It is a statistic technique designed to test for significant relationship between two variables organized in a bivariate table. It requires no assumptions about the shape of the population distribution from which a sample is drawn. However, like all inferential techniques, it assumes random sampling. It can be applied to variables measured at a nominal and/or ordinal level of measurement. The formula for computing Chi-square statistic is given by;

$$X^2 = \Sigma(O-E)^2/E \qquad 7.1.4$$

Where, O = observed frequency, and E = expected frequency.

The essence of the Chi-square test is to compare the observed frequencies with the frequencies expected for independence. If the frequency between the observed and the expected is large, then we reject null hypothesis of independence.

The degree of freedom is given by;

$$Df = (r-1)(c-1) \quad 7.1.5$$

Where, r = the number of rows, and c = the number of columns.

Data collected were subjected to statistical analysis using the SPSS computer package. The Chi-square analysis was conducted at the 5 percent (0.05) level of significance, and the *p*-values for all the observations obtained.

7.3 Results and discussion

The data collected for structured CV questionnaire administered to 420 randomly selected households from the 6 local government areas within the Kano metropolis is presented. Here, the descriptive statistics are presented first and discussed, followed by the inferential Chi-square analysis.

7.3.1 Descriptive Analysis

7.3.1a Socio-economic and demographic characteristics.

The socio-economic and demographic characteristics of the respondents such as age, gender, marital status, education, occupation and family size were analysed and interpreted using descriptive statistics in terms of frequency distribution and percentage (Tables 7.3 (a) and (b)).

Table 7.3 (a): Socio-economic and demographic characteristics

Variable	Frequency	Percentage
AGE (Years)		
18-25	16	3.81
26-35	77	18.3
36-45	133	31.66
46-55	107	25.48
Above 55	87	20.71
GENDER		
Male	298	70.95
Female	122	29.05
MARITAL STATUS		
Married	384	91.43
Single	23	5.47
Separated/Divorced/Widowed	13	3.1

Table 7.3 (b): Socio-economic and demographic characteristics

Variable	Frequency	Percentage
EDUCATIONAL LEVEL		
Tertiary	137	32.62
Secondary	148	35.24
Primary	55	13.1
Informal	80	19.05
FAMILY SIZE		
None	28	6.67
1-3children	115	27.38
4-6 children	101	24.05
7-9 children	103	24.52
10 and above	73	17.38
INCOME		
Less than N18000	33	7.86
N18000-N45000	95	22.62
N45000-N95000	144	34.29
N96000-N120000	79	18.81
N121000-N200000	32	7.62
N201000- N500000	27	6.43
Above N500000	10	2.38
OCCUPATION		
Civil service	108	25.71
Farming	94	22.38
Trading	126	30
Others	92	21.9

Source : Author's field work, 2014

i. Age distribution of the respondents.

As presented in Table 7.3, 31.66 % of the sample households are in the middle age range 36 – 45; 25.48 % of the respondents are between 46 – 55 years, 20.71 % of the respondents are over 55 years. The age distribution also reveals that above 18.20 % and 3.8 % of the respondents' age ranged between the age of 26 to 35 and 18 to 25 years respectively. The data provides a clear reflection of an urban population in which a higher percentage of the populace fall within the middle age group with a majority falling between 36 and 45 years. The mean age of the study is 43.3 years, which indicates clearly that the respondents are at their peak or at active productive age and therefore, can work to earn more income, which affects the decision to pay for newly improved energy commodities. This is similar to findings of Yusuf *et al.* (2012) in his work on the WTP for an improved collection system.

ii. Gender Distribution of the respondents

Table 7.3 reveals 70.95 % of the respondents are male, and 29.05 % are female. This reflects a traditional view and culture of the people in Hausa land in which the males are the heads of the household and assumed to cater for the needs of the family, hence have more responsibilities towards managing the energy requirements/needs within the household.

iii. Marital status of respondents

From Table 7 it is seen that 91.43 % of the respondents are married and 5.47 % are single, while 3.10 % are separated. Looking at the age distribution it can be seen that less than 3.8 % of the population fall below 25 years and 20 % are above 55 years.

iv. Educational qualification of the respondents

As shown in Table 7.3, it is clear that majority of the respondents (35.24 %) had secondary education. They are closely followed by those that attended tertiary education (32.62 %). The informal education is represented by about

19 % of the respondents while only about 13 % had primary education. These results imply that the majority of the households sampled had a formal education with at least an average level of awareness of their environment.

v. Family size:

From Table 7.3, only about 7 % of the respondents have no children, but the majority of the respondents have a family of 1 – 3 (27 %) children. Households with 4 – 6 and 7 – 9 numbers accounts for about 24 % and 25 % of the respondents indicating that about 50 % of the household have a family size of between 4 – 9 members. A large family size of 10 and above members accounted for 17 % of the respondents. This implies that there is a moderate growth in family size, and households are liable to utilise more energy fuel products for cooking and other domestic uses. It also shows that because the majority of the residents in Kano metropolis are married and have children, demand for energy for domestic utilities is expected to be high and scarcity or high cost of energy fuel commodities probably have an effect on the living cost and directly can lead to seeking other options of cheaper options. Income of the respondents

From Table 7.3 about 8 % of the respondents earn less than ₦ 1800 monthly (below £80). Above 29 % of the respondents earn between ₦ 1800 and ₦ 45,000 (£69 - £173) monthly. The majority of the respondents (about 34 %) earn between ₦ 45,100 and ₦ 95,000 (£173 – £365) monthly, while about

15% earn N96, 000 - N120, 000 (£369 - £462) and 7.62 % earn N121, 000 – N200, 000 (£465 - £769).only 769). Only a few percentages of the respondents (about 2 %) earn above 500,000 (£1923).

Occupation of the respondents

In Table 7.3 other forms of occupation, e.g. artisan, mechanic, plumber, etc., account for around 22 % of the respondents. About 30 % of the respondents are traders, 25.71 % civil servants and 22.38 % engage in farming.

The mean values, standard deviation as well as the minimum and maximum values of the age, education family and income distributions of the households were calculate and presented in table 7.4. This values were used the statistical analysis in order to ascertain the significance of each variable in the decision making of willingness to pay for the newly introduced cassia tora pellets.

Table 7.4: Summary of some descriptive statistics

Variables	Mean	Std. dev.	Minimum	Maximum
Age	42.531	14.189	0	1
Education	2.048	0.8674	1	3
Family	5.45	3.708	1	10
Income	87983.333	60245.5	9000	350000

Source: Author’s computations

7.3.1b Energy fuel commodities' availability and supply in Kano

i. Problems associated with energy resources and supply.

From Table, 7.5 households responded to the question of energy supply or resources available for use in domestics or other applications. A very high percentage of 97.3 % agreed that there was limited or no supplies of electricity and other resources, like gas and kerosene, are scarce or mostly not affordable. The only available means is fire wood, corn/maize stover, and other dried agricultural waste plants like cassia tora stems. Only 2.62 % of the respondents are of the opinion that there is no problem associated with their domestic energy supply. This implies that there is a poor supply of energy to the metropolis of Kano state and where other resources are available, they are purchased at high cost.

Table 7.5: Problems associated with energy / energy fuel commodities supply

Variables	Frequency	Percentage
Problem of energy supply		
Yes	409	97.38
No	11	2.62
Concern about distribution		
Not known	15	3.57
Not concerned	23	5.48
Less concerned	115	27.38
Very concerned	267	63.57
Effect of source Proximity to supply		
Yes	368	87.62
No	52	12.38
Closeness to product		
Yes	289	68.81
No	131	31.19
Effect of present product on environment		
Yes	270	64.29
No	150	35.71
Problem of storage		
Yes		
No	244	58.1
	176	41.9
Product satisfaction		
Yes	272	64.76
No	148	35.24
Acceptance of new product		
Yes	297	70.71
No	123	29.29

Source: Author's field work, 2014

ii. Concern about energy distribution

Respondents were asked to express their concern on issues of energy distribution pattern and supply in the country for domestic and other applications, where 63.5 % were very concerned. Only about 5 % of the respondents were not concerned about the energy supply, while 3.57 % had nothing to express. This implies that people's awareness on the issue of energy supply is high and household WTP for better resources such as the fuel pellets is possibly high.

iii. Storage problems with regard to the present energy commodities.

The respondents were asked to assess the problem of storage with energy fuel commodities in use and 58 % agreed that they have a problem on how to store commodities such as fuelwood. About 42 % have no problem with age.*)*

iv. Acceptability of the fuel pellet

From Table 7.5, it is clear that the respondents are willing to accept and pay for the new pellet (70.7 %) with the advantage of storage and other flexibility in usage. About 29 % of the respondents are satisfied with the commodities they are already using. This implies that cassia tora fuel pellets will gain acceptability by households.

7.3. 1c Willingness to pay

From Table 7.4 82.86% of the respondents are willing to pay for the proposed cassia tora stem fuel pellets while 17.14 % are not. A follow-up question indicated that some arguments advanced by the respondents for not WTP include, satisfaction with the energy fuel commodities they are already using, due to economic hardship in terms of unemployment or low level income. The respondents' high percentage of WTP has shown or reflects the value the households are prepared to accept cassia tora fuel pellets instead of, for example, fire wood and corn stover.

Table 7.6: Willingness to pay (WTP)

Variable	Frequency	Percentage
WTP		
Yes	348	82.86
No	72	17.14
Cost of WTP		
Yes	328	78.1
No	92	21.9
Reason for not willing to pay		
I can't afford to pay	63	68.5
I don't readily accept new product	19	20.7
I am satisfied with the old product	10	10.8
Type of product used		
Fire wood	265	63.1
Corn/ maize stalk	98	23.33
Kerosene	52	12.38
Gas	5	1.19
Purchasing method		
Bulk (large quantity)	103	24.52
Few measures (retail quantity)	317	75.48
Marketing agency		
Public agency	78	18.57
Community organizations	54	12.83
Private company	282	67.14
Others	6	1.43

Source: Author's field work, 2014

i. Effect of cost of WTP

In Table 7.6 the respondents were asked how willing they are to pay N1392 per tonne of cassia tora stem fuel pellet, and 78.10 % of the households were WTP and change to the new product, while 21.90 % were not willing to do so. It can also be seen, that for the 92 respondents (68.5%), where cost was considered too high, that lower income plays a role amongst those not WTP for the given amount. Those satisfied with the old supply are about 11 % and those with the opinion that they are not ready to accept the new product are about 20 %. It can be deducted that most respondents probably will accept the new pellet if there is a significant difference in cost (e.g. compared to fuelwood) and other values.

ii. Energy commodities used

It is evident from Table 7.6 that the respondents mainly use fire wood (63.1 %) as a source of heating for domestic and other applications. Maize/corn stover accounts for 23.3 %, while kerosene accounts for 12.38 % and gas 1.99 %.

iii. Fuel pellets purchase method

The respondents were asked to choose between buying the fuel pellets in large or small quantities, with larger quantities supplied at lower cost. It can be seen from Table 7.6 that 75.48% of the respondents preferred to buy in small quantities and only 24.52 % can afford to buy in bulk. This can be attributed to the income level of the respondents and availability of storage space.

iv. Fuel pellets production and delivery services

it can be seen, from Table 7.6 that the respondents prefer the production of the pellets and delivery be done by a private organization (67.14 %) while those of the opinion that 'Government' should handle the issues are 28.3 % and 1.43 % of the respondents prepare the community to handle the issue.

Table 7.7: Maximum WTP per tonne of cassia tora pellet€

Maximum WTP amount(₦)	Frequency	Percentage
500	23	6.76
600	12	3.53
800	4	1.18
1000	44	12.94
1200	30	8.82
1400	87	25.59
1500	79	23.24
1700	28	8.24
2000	14	4.12
2100	6	1.76
2500	13	3.82
Total	340	100

Source: Author's field work, 2014

7.3.1d Maximum WTP amount

The respondents were also asked to state the maximum amount of money they are WTP for the fuel pellets. As presented in Table 7.7, the minimum amounts households are WTP is N500 and the maximum is N2500. The results obtained from the Table were used to determine the household's mean amount of WTP as N1361.471. This is given in Table 7.8. It can therefore be concluded that the sampled households in the Kano metropolis are WTP an average of N1361.471 for the cassia tora fuel pellets.

Table 7.8: Summary of Maximum WTP

Mean	Standard Deviation	Minimum	Maximum
1361.471	646.42	500	2500

Source: Author's field work, 2014

7.3.2 Inferential Chi-square analysis

In Table 7.9 the Chi-square analysis of the households' response to the CV questionnaire is given. The p-values for all the variables are less than 0.001 except for the question associated with the problem of storage. At a 0.05 level of significance it is clear that all variables have a significant effect on the types of fuels used by the households.

Table 7.9: Summary for the chi-square analysis of the household's responses to CV questionnaire

Variable	Min.exp.freq.	Chi-square[a]	Difference	p-value
Problem of energy supply	210	377.152	1	0
Concern about distribution	105	392.076	3	0
Effect of proximity	210	237.752	1	0
Closeness to product	210	59.438	1	0
Effect of product on environment	210	34.287	1	0
Problems of storage	210	11.01	1	0.001
Product satisfaction	210	36.61	1	0
Acceptance of new prod.	210	72.086	1	0
	WTP			
Willing to pay for new prod.	210	181.371	1	0
Cost of WTP	210	56.467	1	0
Reason for not willing to pay	44.3	19.414	2	0
Type of fuel used	105	366.267	3	0
Purchasing method	210	109.038	1	0
Marketing agency	105	423.429	3	0
Maximum WTP	38.2	379.857	10	0

Source: Author's computations

7.4 Conclusion

Socio-economic and demographic characteristics of a household have an influence in household's decision making in WTP for a newly introduced product or improved services. Other factors influencing such decision are availability, supply and storage of the present energy fuel commodities used by the households. The unit production cost of cassia tora stem pellets was estimated to be at ₦ 1286.4/t or £4/t. At a profit margin of 30 % the selling price is established at ₦ 1672.32/t. From the analysis of maximum amount of WTP, it is deduced that households in the Kano metropolis are WTP ₦ 1361.5/t for the cassia tora stem fuel pellets,

8. DISCUSSION SUMMARY

8.1 Introduction

Fuel wood is the predominant energy source in Nigeria, accounting for about 80 percent of the entire energy consumption. An estimate of 50 million metric tons (t) of wood is consumed annually, resulting in deforestation, desertification, soil erosion and loss of soil fertility (Momodu, 2013; Edward and Paul, 2013; Sambo, 2005). About 70 to 80 percent of the households in Nigeria use fuel wood as a source of domestic energy, which accounts for over 50 percent of the total energy consumption in Nigeria (Momodu, 2013; Sambo, 2006). Crop residues and waste annually produced in Nigeria amount to 6.1 million metric tons with potential energy content of $5.3x10^3$ MJ (Okoroigwe, 2008). According to the Kano State Ministry of Agriculture (KNMANR, 2014), a substantial part of the crop residues/waste is from cassia tora plant remains, a known farm weed that grows in every unattended and cultivated land in the entire Kano state and North-western region. Densifying such plant material into energy products like fuel pellets is one of the best ways of solving the problem of energy supply within the region. This makes it a potential sustainable alternative to wood fuel and other fossil fuels as a source of energy. High-quality fuel pellets have high durability, low pollutant emission during combustion or gasification and a high calorific value (Huang, 2009). Low bulk densities have a negative effect on the energy density and therefore transport cost and storage capacity (Obernberger and Thek, 2004).

8.2 Characteristics of cassia tora pellets (Chapter 3)

The lengths and diameters of the cassia tora pellets, for varied production temperatures and pressures, ranged between 47.35 - 43.70 mm and 14.45 - 14.00 mm, respectively, which are in line with the guiding values of CEN/TC 335, but slightly higher than that of DIN and ONORM standards.

The bulk density was in the range 617.34 – 619.20, for 50 MPa/30^{o}C – 140 MPa/120^{o}C respectively.

Durabilty of fuel pellets should not be less than 98.7% as provided by the standards (CEN/TC; ONORM; DIN). Gil et al. (2010) argued based on experimental experience that durability of 85 % is the minimum for a quality fuel pellet. Comparing this with the result obtained means that all pellets produced at temperatures of 75, 90, 105 and 120^{o}C fall within this range. The durability of cassia tora pellets produced at this temperatures ranged between 85 and 97 %, irrespective of the production pressure.

Moisture content has an influence on the gross calorific value, combustion efficiency and temperature of combustion, biomass fuels with high moisture have problems of ignition and low GCV (Obernberger and Thek, 2004). The moisture content of the cassia tora stem pellets from Chapter 3 as presented in Table 3.4 shows that the pellets produced at high temperature and high pressure conditions have lower moisture content with the least moisture of 7.18 % obtained at 140 MPa and 120^{o}C. The moisture content ranged between 7.18 and 9.6 % for highest pressure/temperature and lowest pressure/temperature, respectively. This is reasonably low and comparable to biomass fuel pellets. The amount of the ash content ranged between 4.2 and4.3 %, which is also within the standard ONORM 7135 specifications for commercial fuel pellets. The variation in the production conditions has influenced the presence of the moisture, especially the increase in the temperature of pellet production which relatively reduces the amount of moisture, which in turn increases the GCV. The results obtained for the GCV ranged between 17.89 and 18.1 MJ/kg from the lowest to highest temperature/pressure conditions of production respectively. The GCV values also fall within the stated values of commercial fuel pellets that comply with Standard's organisations (and referenced in this research). The GCV of cassia tora pellets reasonably comparable to other biomass fuel pellets reported in the literature, where a range 18.05-18.6 MJ/kg was reported by Zamorano *et at.,* 2011) for straw pellets.

The pellets produced within the laboratory frame work of this research at 90Mpa and 120MPa have an average diameters 14.21 and 14.16mm with corresponding lengths of 45.17 and 47.07mm respectively. The ratios L/D is therefore 3.18 and 3.32. Although the diameter is larger than the specification of ONORM and DIN and of course lower L/D ratio, it has been in conformity with CEN/TS specifications since the length is less than four times the diameter and the produced cassia tora pellets' diameter falls within the range of 8 to 25mm. Furthermore, the parametric studies confirms that pellets can be could be made to every standard sizes if cassia tora were to become a traded fuel.

In Chapter 4 thermogravimetic analysis (TGA) data was used in the determination of the pellet's kinetic parameters as supported by literature (Celyn and Topcu, 2014; Ibrahim *et al*., 2013; Pathasarathy *et al*., 2013; Polat *et al*., 2013; Yorulmaz and Atimtay, 2009; Mansaray and Ghaly, 1999). Quantitative methods were applied to TGA curves to obtain the kinetic parameters (Pathasarathy *et al.*, 2013). The TGA data presents about 9.2 % moisture 56.4 % cellulose 30.4 % lignin and no further thermal deformation was achieved above 800^{o}C leaving behind 4.2 % ash and is almost certainly inorganic in nature.

The maximum weight loss occurs at the temperature range of 630 to 708^{o}K and when compared to results obtained in the literature, Rajeswara and Sharma, (1997) reported a maximum weight loss at 573 to 723^{o}K , Mansaray and Ghali, (1999) found out that 740 ^{o}K is the maximum weight loss temperature for rice husk.

Nitrogen (N); the specification for the amount of nitrogen content for ONORM and DIN is less than or equal to 0.3% and for CEN/TS is between less than equal to 0.5 and 3% and normative only for chemically treated biomass. The content of nitrogen as presented in Chapter5 is 1.48% which is expected of straws and grass pellets as with case of cassia tora pellets.

Sulphur; the specification for sulphur by ONORM is less than 0.04% and DIN is less than .08%, where as that of CEN/TS varies between less than 0.05 and 0.2 normative to chemically treated biomass and if sulphur containing additive is used as a binder. The content of sulphur as presented in Chapter 5 is 0.21%. This has been in conformity with the highest level of sulphur expected from CEN/TS specification. The content of the 0.122% which is low and cannot be ascertain to have incremental effect on the sulphur content of the cassia tora pellets.

8.3 Economics of production

Taking a base case pellet plant with a production capacity of 5 t/h cassia tora and an annual production of 32,400 t and assuming the plant operates for 270 days annually (annual utilisation period of 74 %) the operating and total production costs were calculated to be 35 million Naira (£131,350) and £4.755/t. A production cost of ₦ 1286.4/t for conditions found in Nigeria, is economically viable when compared with values available in the literature for other countries, where Mani *et al.* (2006) reported a case ₦ 6529.6/t (exchange rate of ₦ 220 to 1$) and Anthony et al. (2011) reporting ₦ 2244/t.

The contingent valuation method was employed to determine the household's willingness to pay (WTP) for the pellets. About 82.86% of the respondents were WTP for the proposed cassia tora stem fuel pellets while 17.14 % were not. A follow-up question indicated that some arguments advanced by the respondents for not WTP included satisfaction with the energy fuel commodities they are already using and constraints due to low income. The respondents' high percentage of WTP shows the value the households are prepared to accept for use of cassia tora fuel pellets instead of, for example, fire wood and corn stover.

With the problem of inadequate supply energy commodities coupled with environmental problems, pellet production In Nigeria will significantly contribute in the nation economic development by providing investment opportunities and job creation. Environmental issues with regards to combustion of fossil fuels and felling of trees for fuel wood will also be addressed.

In general the properties of the cassia tora pellet can be classified according to its' physical and chemical properties. The summary is presented in tables 8.1 and 8.2.

Table 8.1: physical properties cassia tora pellets

pellet parameter	90MPa at 90°C	120MPa at 90°C	140MPa at 90°C	Remarks
Diameter (mm)	14.2	14.2	14.04	Higher than ONORM and DIN specification in all cases but fall within CEN/TS specifications
Length (mm)	45.1	45.1	44	Same as with diameter
Part. Den.(g/mm3)	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	Conforms with the range of specification of ONORM and DIN
Durability (%wt)	93	-	95	Durability is below the standard of ONORM and DIN but falls within the specification of CEN/TS

Table 8.2: chemical properties of the cassia tora pellets

pellet parameter	90MPa at 90ºC	120MPa at 90ºC	140MPa at 90ºC	Remarks
Moisture (%w.b)	8.02	-	7.23	Moisture is in conformity with all standards
Ash content (%wt)	4.2	-	4.3	Ash content conforms only within the specification of CEN/TS
GCV (MJ/kg)	18.09	-	18.09	Pellets gross calorific value conforms with all the standards
N (% wt)	1.48	1.48	1.48	Nitrogen content is high as compared to ONORM and DIN but is within the range of CEN/TS specifications
S (% wt)	0.21	0.21	0.21	Sulphur content is only within the specification of CEN/TS
Cl (% wt)	0.32	0.32	0.32	Chlorine is high as compared with all standards

At a willingness to pay price of 1550 Naira, a possible pay-back period of 6 years can be achieved in a case scenario production of 5t/hr of cassia tora pellets

9. Final conclusions

The research programme has achieved the objectives stated in Section 1.5, and the following conclusions can be made;

1) Cassia tora pellets were successfully produced in a laboratory scale experiments, under varying temperature/pressure conditions with gum arabic as a binder. Temperature significantly influences the production of quality pellets, with higher temperatures enabling better pellets to be produced, e.g. with respect to durability. The mould adopted has flexibility in use with different compression equipment.
2) Cassia tora pellets were proven to be a suitable combustion fuel because: (i) the GCV of cassia tora pellets are between 17.89 MJ/kg and 18.1 MJ/kg, making them comparable to other biomass fuel pellets; (ii) moisture between 7.18 and 9.60 % (w.b.), which is sufficiently low and therefore will not cause ignition problems during combustion; (iii) the ash content of the pellets is within the range 4.2 to 4.3 % (d.b.), which is lower than 5 % as provided by ONORM standards; and (iv) no toxic elements were detected, either in the raw materials or the ash.
3) Pellets produced at high temperatures have high durability and therefore will not cause problems in combustion equipment.

4) It can be concluded that cassia tora pellets should be produced at a temperature range of 60 to 90^{o}C, with production pressure of 120MPa, and 6 to 8% by weight binder addition.
5) TGA analysis results reveal 9.2 % moisture, 4.2 % ash, 56.4 % cellulose and 30.4 % lignin. The activation energies calculated at various thermal distortion stages are 72.01, 106.81 and 88.67 kJ/mol for stages I, II and III respectively. These values are comparable to other biomass fuels and therefore provide further proof of the suitability of cassia tora pellets as a fuel.
6) A bulk density of about 618 kg/m^3 is similar to commercially available pellets and makes pelletisation of cassia tora stems viable with respect to the cost of transportation and storage.
7) Cassia tora stems are harvested dry and therefore have the advantage of not requiring drying equipment during pelleting.
8) Storage had only minor affects on the properties of the pellets, and not of practical significance.
9) A total capital cost of 35 million Naira (£131,350), with a unit cost of 1094.57 Naira/t (£4/t) was evaluated in the cost analysis of pellet production for conditions found in Nigeria. This is economically viable when compared with values available in the literature for other countries.
10) A contingent valuation method employed to investigate households' willingness to pay for pellets was successful and the households were willing to pay for the maximum amount stated.

11) In order to encourage investment with respect to pay-back period, a selling price of1800 Naira at a profit margin of 40% is recommended.

10. Recommendations for further work

In the course of meeting the main objectives of the research, new avenues of research can be seen.

1) Though the combustion properties of the pellets have been investigated and were found to be closely comparable, and competitive, with other biomass fuel pellets, ideally, practical combustion in a fluidised bed combustor would lead to a fuller understanding of the pellets combustion efficiency and assess its carbon monoxide emissions. However, this type of equipment is expensive, both to access and provide the quantity of fuel necessary in a trial. Access to this type of equipment would also enable a thermodynamic model to be developed in order to predict the gaseous emissions and depositions produced from the combustion of the pellets.
2) Addition of gum arabic has an effect on the quality of the fuel and on storage and the effects of gum arabic on the pellet's compressive strength and its behaviour over a period of time justify further work.
3) Cost of pellet production was investigated based on the assumption of cassia tora plants being collected as part of solid waste. However, an investigation into the economics of harvesting cassia tora plants as a raw material should be carried out in order to have a fuller understanding of its potential use for commercial pellet production.

4) The pellets have potential use as a source of fuel for a Stirling engine to provide either mechanical work or electricity generation. This could be investigated and help in understanding the wider industrial application and economic benefits of cassia tora fuel pellets. The Stirling engine could for example power the pelleting plant. A low cost solution would be ideal for Nigeria.
5) Energy policies and investment should be geared towards commercial pellet production to help achieve reductions in environmental deterioration, and developments in economy and energy sustainability in Nigeria. The work undertaken and discussed in this thesis provides good investment information to inform the Nigerian and Kano state 'Governments'. The pellet production plant proposed could also be used for other biomass materials instead of or with cassia tora.
6) There is the need for a larger scale storage experiment where sacks are stacked. This will give room for the investigation of the effect of dry matter loss, durability, bacteria activity, change in GCV, effect of humidity and durability, during storage. Also auto-ignition temperature for self-heating risk can be investigated.
7) There is need for investigation of environmental pollutants during combustion. This should bring about the need for emission measurement during use in cook stoves and the impact on ambient air quality.

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Appendices

Appendix 1: Calibration materials

Reference	Material	Expected transition	measured transition
0098-8015	Alimel calibration ref.	154.2ºC	152.8oC
0998-8016	Nickel calibration ref.	355.3oC	351.0oC
0998-8018	Perkalloy calibration ref.	596oC	597Oc

Appendix 2: Spectrographic analysis of reference materials

Alumel	
Material	Analysis
Nickel	94.45%
Manganese	1.98%
Aluminium	1.26%
Cobalt	0.50%
Magnesium	0.04%
Iron	0.02%
Copper	0.002%
Zirconium	0.00%
Nickel	
Material	Analysis
Nickel	99.995%
Copper	10 ppm
Perkalloy	
Material	Analysis
Nickel	74.74%
Iron	24.25%
Silicon	30 ppm
Copper	10 ppm

Appendix 3

QUESTIONARE

PRODUCTION AND CHARACTERIZATION OF FUEL PELLETS FROM CASSIA TORA STEMS (TAFASA IN HAUSA) FOR DOMESTIC AND INDUSTRIAL APPLICATIONS

Dear respondent

I am a PhD student of the Department of Mechanical Engineering, University of Wolverhampton United Kingdom. I am conducting a research on the topic **‘’ production and characterization of fuel pellets from cassia tora stems (tafasa in Hausa) for domestic and industrial applications’’** An economic validation of the pellets production for domestic and other application in Kano, Nigeria is sought. I solicit your assistance and cooperation to honestly and accurately respond to some questions that would assist policy makers and other stakeholders in determining the economic validity of the pellets production to improve on the present inadequate supply of energy resource in the state and the country in general. Your opinion is therefore very important and also I am assuring you that all your answers are to be treated confidentially.

I am thanking you for your anticipated cooperation.

THE PRESENT STATE SUPPLY OF ENERGY FOR DOMESTIC AND OTHER APPLICATIONS IN KANO STATE

As you are aware there is inadequate supply of energy for domestic and other applications in Kano state and the country in general, the source available are either scarce or if locally provided have environmental effect with no good method of storage. If another product is provided that is well packaged to take care of the storage and environmental sanitation problems but with more cost attached, what would be your response to this new development? I would therefore ask you some questions related to these issue.

1. In your opinion do you think inadequate supply of energy is a problem in Kano state?

a) yes ( )

b) No ( )

2. Are concerned about the present indiscriminate distribution of energy resource/power practice?

a) Not known ( )

b) Not concerned ( )

c) Less concerned ( )

d) Very concerned ( )

3. In your opinion what is the problem of energy supply in your area.

……..

4) Do you believe closeness to sources of energy plays a role in this inadequate supply?

a) Yes ( )

b) No ( )

5) Are close to any major or local source of energy that is used within your locality?

a) Yes ( )

b) No ( )

6) Does the use of the present energy product have impact on your environment? Example; waste generation and pollution.

a) Yes ( )

b) No ( )

7) Is storage of the product a problem to you in your household?

a) Yes ( )

b) No ( )

8) Would you derive any satisfaction from using the new product?

a) Yes ( )

b) No ( )

9) Do you want the provision of any new energy product in the state?

a) Yes ( )

b) No ( )

WILLINGNESS TO PAY

There is plan to produce an improved energy fuel product from Cassia tora stem (tafasa) to be used as an alternative or to supplement the present products but you are expected to pay more for this improved product. I would like to ask you more questions to understand your preference.

10) If you are provide with this new product are you willing to pay more for it?

a) Yes ( )
b) No ( )

11) The cost of the fuel pellet is between N1550.00 to N1650.00 per ton, would you be willing to pay?

a) Yes ( )

b) No ( )

12) What is the reason you do not want to pay more for the product?

a) I can't afford to pay ( )

b) I don't readily accept new product ( )

c) I am satisfied with the old product ( )

13) What is the maximum amount that you are willing to pay for the product in Naira?

…………………………………..

14) What type of energy product do you use in your household?

a) Fire wood ( )

b) Corn/ maize stalk ( )

c) Kerosene ( )

d) Gas ( )

15) How do you buy the energy products used in your household?

a) Bulk (large quantity) ( )

b) Few measures (retail quantity) ( )

16) If you are willing to pay for the new product, whom do you prefer to produce and provide the product for sale to you?

a) Public agency

b) Community organizations

c) Private company

d) Others, specify …………………………………….

SOCIO-ECONOMIC AND DEMOGRAPHIC CHARACTERISTICS

17) Gender

a) Male ( )

b) Female ( )

18) Age

a) 18-25 years ( )

b) 26-35 years ( )

c) 36-45 years ( )

d) 46-55 years ( )

e) Above 55 years ( )

19) Marital status

a) Married ( )

b) Single ( )

c) Separated/ Divorced/ Widowed ( )

d) others, specify ……………………………………

20) Level of education

a) Tertiairy education ( )

b) Secondary education ( )

c) Primary education ( )

d) Informal education ( )

21) What is your occupation?

a) Civil service ( )

b) Trading ( )

c) Farming ( )

d) Others ( )

22) What is the estimate of your monthly house hold income in Naira?

a) Less than N18000 ( )

b) N18000-N45000 ( )

c) N45000-N95000 ( )

d) N96000-N120000 ( )

e) N121000-N200000 ( )

f) N201000- N500000 ( )

g) Above N500000 ( )

23) Number of children

a) None ( )

b) 1-3 ( )

c) 4-6 ( )

d) 7-9 ( )

e) 10 and above ( )

Thank you Sir/Madam your response will be treated with outmost confidentiality.